Akad. Geowiss. Geotechn., Veröffentl., **28** (2011): 39 - 62

Akademie für Geowissenschaften und Geotechnologien e.V.

Estimates of Mineral Resource Availability – How Reliable Are They ?

Hartwig E. Frimmel & Jürgen Müller

Abstract : Forecasts for a number of non-renewable commodities were modelled using actual resource and reserve data on the one hand and extrapolating historic production cycles into the future on the other hand. The former approach proved useful for medium-term forecasts whereas the latter is more appropriate for long-term forecasts, provided the production cycle of a given commodity has reached maturity. The extent of maturity can be quantified by the ratio of annual production/cumulative production. Long-term forecasts can be obtained by applying various sigmoid functions of which the Richards Function yielded the most realistic results.

The specific examples used in this study show that the peak in global crude oil production is being reached now, similarly to global phosphate and gold productions both of which have reached a plateau with little potential for significant future growth. The contribution from the world's historically by far most important gold producer, South Africa, to the future global gold production will decline into insignificance by the mid-2020s. In contrast, continuation of current exponential growth in the global Cu and rare earth element production is projected and no meaningful long-term availability forecasts can be made. The other extreme is represented by Hg for which the global production cycle has effectively come to an end, i.e. the global resource is almost depleted. Global U supply is modelled to be more than sufficient to meet expected demands in the medium-term (next 15-20 years) but will fall short of meeting this demand from the 2030s onward. Thermodynamic constraints will limit the utilisation of long-term future „unconventional resources" as the energy required to extract the desired commodity from such resources, which are typically of very low grade, will be too high. As mining companies are likely to carry more and more of the currently external costs of mining, following an anticipated pressure to conform to sustainability reporting standards, the proportion of current resources turning into future reserves will decrease. Trends over the past few decades show that increasing commodity prices, following anticipated shortages and subsequent increases in exploration expenditure do not necessarily lead to an expansion of the reserve base as commonly perceived. For those commodities whose production cycles have reached maturity, the development of substitutes and more efforts towards a sustainable usage by improved recycling will be imperative in order to avoid future society-threatening shortages.

1 Introduction

Most mineral resources are believed to have formed over such long time-spans that they have to be considered non-renewable. Exceptions might be, for example, rock salt that can precipitate in shallow coastal pans at a rate that corresponds to the rate of exploitation for the production of table salt. Many industrial mineral deposits of sedimentary origin were laid down typically over extended periods in the order of 10^5 to 10^6 years, those related to plutonism might have formed in shorter time intervals but it typically takes millions of years to expose these rocks to the surface and thus render them suitable for mining. Some metallic mineral deposits formed over considerably shorter periods. For example, it has been estimated that one of the world's largest epithermal gold deposits, Ladolam on Lihir Island, has formed in less than 55 000 years (Simmons & Brown, 2006). Mineralisation there is on-going with a Au flux of 24 kg/a, but this is by far not sufficient to replenish the ore deposit that is currently mined at a rate three orders of magnitude higher (25 t/a in 2010).

Without any doubt, the exploitation of mineral deposits is one of the most fundamental pillars of modern societies with economies in effectively all countries being highly dependent on the supply of raw materials from such deposits, be it for energy or for industrial production. Considering the exponential increase in world population over the last century, it is not surprising that the question of the limits to the exploitation of non-renewable resources has been raised repeatedly throughout that time.

Contact: Prof. Dr. Hartwig E. Frimmel[1,2], Dr. Jürgen Müller[2,3]

1) Department of Geological Sciences, University of Cape Town, Rondebosch 7701, South Africa

2) Geodynamics & Geomaterials Research Division, Institute of Geography & Geology, University of Würzburg, Am Hubland, D-09074 Würzburg, Germany

3) Einkaufsgemeinschaft für Gold und Silber GbR, Gartenstrasse 28, D-89547 Gerstetten, Germany

With the legendary book "The Limits to Growth" (Meadows et al. 1972), commissioned by the Club of Rome, the problem of limited availability of non-renewable resources for a growing number of people on Earth has been widely popularised. In subsequent years an unprecedented spur in exploration and subsequent discoveries combined with technological advances led to a drastic increase in supply and consequently to a fall in many commodity prices, which lulled many economists as well as politicians into a sense of security with regard to future mineral and energy supply. "The Limits to Growth" was more and more regarded as "doomsday prophecy" instead of being taken as timely warning. Even today organisations, such as the World Nuclear Association, describe it as "Limits to Growth fallacy, a major intellectual blunder recycled from the 1970s" (WNA 2010). However, since the beginning of this century the situation has changed dramatically. Staggering economic growth in emerging markets, foremost China, India and Brazil, has led to fierce competition for several mineral and energy resources worldwide. Accordingly, almost all commodity prices have seen a steady incline since 2004, reaching peaks in 2008 prior to the global financial crisis. This upward trend might have been interrupted by that crisis but surely not stopped. Most commodities have been approaching peak price levels again over the past year (Fig. 1).

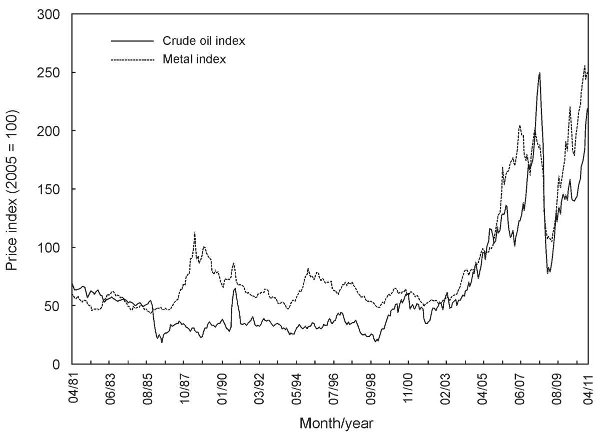

Fig. 1: Historic price trends for selected mineral and energy commodities (price index for 2005 = 100): Metal price index includes Cu, Al, Fe, Sn, Ni, Zn, Pb and U price indices, crude oil price index is the monthly average of three spot prices (Dated Brent, West Texas Intermediate, and the Dubai Fateh); data from the International Monetary Fundd (retrieved from www. indexmundi.com/commodities).

Today the limits to a sustainable exploitation of conventional non-renewable energy resources is widely recognised by the general public with discussions around "peak oil" having profound consequences on wide-ranging political decisions. Although much of this discussion is hidden behind the debate on global climate change and the desire to reduce greenhouse gas emissions, the ultimate challenge is to replace, in time, our dependence on the non-renewable energy resources oil, gas and uranium ore (coal is less of an issue in this context as it is far more abundant and is already being used to compensate for a decrease in oil production) rather than to slow down global warming. Current public awareness is, however, more sensitised towards measures to fight global warming. As the increase in (largely anthropogenic) atmospheric CO_2 only commenced decades after the most recent cycle towards higher global temperatures, which began in the 1860s (Leuliette et al. 2004, Oerlemans 2005, Jevrejeva et al. 2006), the connection between anthropogenic CO_2-emission, largely from the burning of fossil fuels, and increase in global temperature remains far from proven (Robinson et al. 2007). Fortunately, the practical consequence of these debates remains the same, irrespective whether one believes in anthropogenic CO_2-triggered global warming: we have to strive towards drastically reducing fossil fuel consumption.

While there might be general agreement on the principal aim, i.e. reducing our dependence on fossil fuels, huge differences in opinion exist regarding the urgency in changing our habits of energy resource consumption and the extent to which this aim should be reached. Have we reached "peak-oil" already or can we carry on with "business-as-usual" for another few decades? Is the peak-oil theory applicable to mineral resources as well or will market forces ensure that mineral resources can be exploited indefinitely, with increasing prices and technological advances making possible the exploitation of much lower-grade ores? The answers to these questions are complex but fundamental for the future of our well-being on Earth.

Apart from the well publicised issues around fossil fuels, there are a number of non-energy raw materials that more recently have come into the spotlight as concerns have risen about potential shortages. Foremost amongst them are the so-called high-tech metals that are essential for a series of modern and future environmentally friendly products, such as lithium and neodymium for electric cars, or indium, gallium, selenium and tellurium for solar panels. The significance of the topic of raw material availability is reflected inter alia by the European Commission having established a Raw Materials Supply Group that was tasked with identifying a list of critical non-energy raw materials as well as with the assessment of their level of criticality (RMSG 2010). Note that no fewer than 14 out of the 41 minerals and metals considered in that study have been classified as "critical", i.e. the risks of supply shortage and their impacts on the economy are considered higher than those of most of the other raw materials. A number of recent policy papers by national and provincial governments on the issue of securing the supply of raw materials to national or regional industry (e.g. BMWi 2010) further highlight the growing recognition of the importance of the issue of future supply with non-renewable raw materials.

The various studies on the future availability of non-renewable raw materials follow vastly different philosophies and methodological approaches – resulting in highly different assessments. The methods used range from statistical methods, based on past production trend extrapolations, to the determination of ultimate reserves, combined with various future demand scenarios. The differences in the methods employed severely hamper the usefulness of the resulting predictions as base for future policy-making. To provide some answers to the above questions and in an attempt to bridge the gap between apparently inconsistent predictions on the future availability of non-renewable mineral resources, we shall assess in this paper various ways of forecasting production trends and availability of these resources. For practical reasons we distinguish between short-term (up to 10 years), medium-term (5 – 25 years) and long-term (>20 years) forecasts, and it will be shown later in this paper why different methodological approaches are necessary to provide meaningful predictions on these different time scales.

Mining is a highly energy-intensive business. In most cases it also requires huge amounts of water. Thus the future of mining is intimately linked with the availability and costs of energy and water supply. As will be discussed in more detail later, future ore deposits will be, in general, of lower grade than those currently mined. In several sustainability studies it has been shown that the energy required for the extraction of metals from ore deposits increases exponentially with decreasing ore grade (e.g. Mudd 2007, Storm van Leeuwen & Smith 2008, Mudd & Diesendorff 2010). Consequently, any forecast on future availability of mineral resources must be heavily dependent on energy resources. We therefore include assessments of the forecasts of non-renewable energy resources, using crude oil and uranium as examples. Examples of non-energy resources used in this study will come from the non-ferrous metal sector (Cu, Hg), the precious metal sector (Au), and from industrial minerals (phosphate rock). We focus specifically on elements that require a high concentration factor from crustal background values in order to reach economic grades ("Clarke Value") as is the case for almost all metallic commodities. Other raw materials, such as limestone, sand or granite, accumulated over much larger areas and in much larger volumes than ore bodies. On a global scale, the availability of these materials is, therefore, not an issue but, bearing in mind the comparatively high significance of transport costs in their beneficiation, their local/regional availability might differ hugely from place to place. They are not considered any further here but it should be noted that in areas of geologically favourable settings, their availability is not a given but might be more dependent on socio-political factors, such as competing demands on land use.

Most of the historic production data used in this study was taken from open files of the U.S. Geological Survey (USGS) as provided on their website (http://minerals.usgs.gov) and the Raw Materials Data Base that can be obtained from the Raw Materials Group (www.rmg.se). If the data used come from any other source, this is indicated accordingly.

2 Extrapolation of historic production curves into the future

2.1 The Hubbert Method

The temporal variation in the production of any non-renewable resource must follow initially an increase in production per unit time until it reaches a maximum ("peak" or "depletion mid-point") that is followed by a decrease in production per unit time. As pointed out by Hubbert (1956), such a variation in production over time should approximate a Gaussian normal distribution or, as he alluded to in later studies (Hubbert, 1982), a logistic function. The latter can be described by a differential equation:

$$dQ/dt = a \cdot Q(t) \cdot [Q_\infty - Q(t)] \qquad (1)$$

where dQ/dt is the annual production of a resource, a is the growth rate, $Q(t)$ the cumulated production at the time t and $[Q_\infty - Q(t)]$ the amount of the resource yet to be produced in the future. In the case of a Gaussian normal distribution, the annual production must reach its peak at $Q = Q_\infty/2$. Thus, the peak production can be determined if the total recoverable amount of the resource (Q_∞) and the growth rate a are known. There are various ways of constraining Q_∞. The simplest approach involves a chart-technical extrapolation of trend lines when the ratio P/Q is plotted against Q as applied by Hubbert (1982) to oil and gas production data. Data from the early production times can be ignored because of a typically huge fluctuation in P/Q when Q is still small. With time, as Q increases, the variation in P/Q decreases and the P/Q ratio approaches a linear trend. Here the principle of the Hubbert Linearisation is exemplified by the South African gold production (Fig. 2).

In South Africa industrial gold mining commenced in 1883 and has been based almost exclusively on the mining of auriferous and uraniferous conglomerates that represent Mesoarchaean placer deposits (Frimmel et al. 2005). As can be

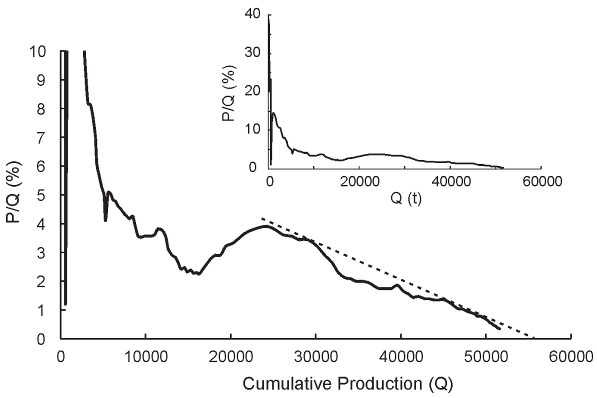

Fig. 2: The ratio of annual production (P) over cumulative production (Q) as a function of Q (in metric tons) for the South African gold production from 1883 to 2010. The variation in P/Q decreases with increasing Q, approaching a linear trend (stippled line) whose intersection with the x-axis gives an estimate of the total recoverable amount of gold from the South African goldfields (Q_∞ = c. 56 000 t Au); data from the South African Chamber of Mines (www.bullion.org.za).

seen from Fig. 2, the *P/Q* ratio decreased substantially to less than 0.5 %, highlighting the fact that the South African gold mining industry has already highly matured after having had reached its peak as early as 1970 when about 1 000 t Au had been produced. From that diagram it can be confidently predicted that the cumulative production (*Q*) to date of 51 553 t Au is already close to Q_∞, which can be extrapolated as c. 56 000 t Au.

An alternative approach to the Hubbert Linearisation is the parabola method. The differential equation (1) can be solved separating the variables of the logistic function as developed by Verhulst (1838) to model population growth, i.e.

$$Q(t) = Q_\infty / (1 + e^{-a(t - t_{peak})}) \quad (2)$$

As pointed out by Hubbert (1982), the simplest mathematical way to describe the conditions of annual production (*P*) being zero at both *Q* = 0 and Q_∞ = 0 is a second-order parabola. Thus, by plotting the annual production *P(t)* as a function of the cumulative production *Q(t)*, and fitting a second-order parabola into the dataset, the intercept of that parabola with the x-axis yields an estimate for the total recoverable amount of the given resource (Q_∞). Approximating the crude oil production of the USA by the first derivation of such a logistic function (Fig. 3) yields an impressively good fit (R^2 = *0.9902*) and illustrates that Hubbert's original prediction of a production peak in 1970 was very close to reality indeed – the actual peak was reached in 1971. For estimates on Q_∞ (crude oil) obtained by this way for 50 different oil-producing countries see Canogar (2006).

Hubbert's approach can also be applied to the

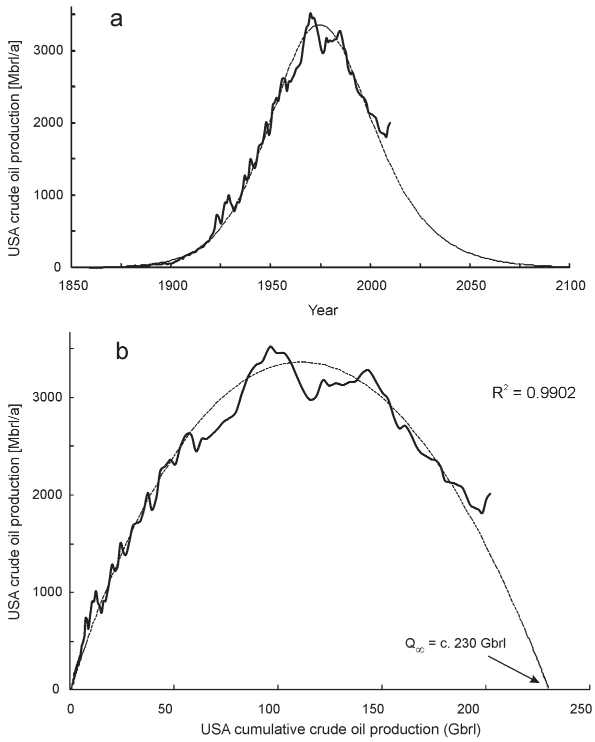

Fig. 3: Annual crude oil production of the USA as a function of cumulative production for the period 1859 to 2010 (bold curve) approximated by a second-order parabola that indicates Q_∞ of approximately 230 Gbrl; data from the U.S. Energy Information Agency (www.eia.gov).

global crude oil production, which since 2004 has reached a plateau at around 26.7 Giga barrel (Gbrl) per year. Approximating the global crude oil production curve by a logistic function (Fig. 4) yields a very good fit (R^2 = *0.9989*) and would suggest a peak in the year 2010, with a peak production of some 27 Gbrl/a. The actual production for 2010, in spite of the Deep Water Horizon catastrophe, was 26.83 Gbrl. Interestingly, already more than 14 years ago Edwards (1997) calculated that "peak oil" should be reached by the year 2010 (± 11 years) and predicted a Q_∞ of 2400 ± 400 Gbrl by averaging 14 different predictions that had been made at that time. The latter value is in good agreement with the Q_∞ of roughly 2300 Gbrl that can be obtained from the parabola shown in Fig. 4.

A production curve that follows a logistic function is obviously an ideal situation. Particularly in the case of individual regions, ore districts or, even more so, on the scale of a single mine, production curves are unlikely to follow such a symmetrical curve with a single peak but will be more irregular. Deviations from the ideal curve can be caused by numerous factors, such as mistakes or breakthroughs in exploration, technological advances, political or economic crises, wars, strikes, cycles in the world economy, changes in legislation, and many others. This can be accounted for by a

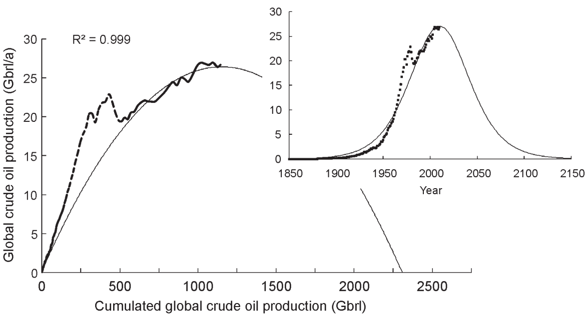

Fig. 4. Global crude oil production as a function of cumulative oil production (bold curve), approximated by a second-order parabola (thin curve) whose intersection with the x-axis suggests a value for Q_∞ of some 2300 Gbrl. The insert shows the temporal variation in oil production, and the best fit curve for Q_∞ = 2300 Gbrl; data from the U.S. Energy Information Agency (www.eia.gov).

multicyclic Hubbert equation as expressed by Al-Fattah & Startzman (2000),

$$q(t) = \sum_{i=1}^{k} q(t)_i = \sum_{i=1}^{k} 4(q_{max})_i \cdot \{e^{-a(t-tmax)}/[1 + e^{-a(t-tmax)}]^2\}_i \quad (3)$$

where $q(t)$ is the production rate at time t, k the total number of production cycles, q_{max} and t_{max} the peak production rate of each cycle and its corresponding time, respectively, and a is a constant. The parameters involved in equation (3) can then be calculating by non-linear least-squares computation. For each production cycle an ultimate recoverable amount Q_∞ can be obtained from the following equation

$$Q_\infty = 4\, q_{max} / a \quad (4)$$

The total ultimate recovery is then obtained by adding Q_∞ for each production cycle. Nashawi et al. (2010) applied the above multicyclic Hubbert Model to 47 major oil-producing countries and thus calculated peak-oil to be reached in 2014 – considerably earlier than many previous predictions but close to our prediction shown in Fig. 4. Overall, they found that 17 % of the evaluated national oil production data yielded excellent models, 70 % very good models and the remaining 13 % what the authors considered good models. Their results also highlight that the modelled forecasts' accuracy increases with progressive production maturity. For example, the modelled forecast for the crude oil production of Norway, similarly to Hubbert's forecast of the USA oil production, is excellent. Norway's oil production reached its peak in 2001. In general, non-OPEC countries have already passed their peak in oil production in 2006, whereas OPEC crude oil production is modelled to peak in 2026 (Nashawi et al. 2010).

Integration of a number of individual mines, ore districts or even national productions should smooth the irregularities mentioned above. The larger the scale at which production is considered, the more production curves should approach a symmetrical curve with one principal peak. Nevertheless, the increase in annual production does not have to take place over the same time span and at the same rate as the post-peak decrease – production curves can be also asymmetric. Assuming that the growth rate a in Equation (1) is itself dependent on time, the postulated asymmetry can be expressed by an additional parameter n in a general Verhulst Function:

$$Q(t) = Q_\infty / [1 + (2^n - 1) \cdot e^{-a\,(t - t_{peak})}]^{1/n} \quad (5)$$

discussed in detail by Roper (1976). An n-value of 1 would imply a symmetrical curve, whereas n <1 and n >1 would indicate a shift of the peak to the left (back in time) or to the right (forward in time), respectively. For example, empirical analyses of numerous crude oil production curves on a regional, national as well as continental scale revealed an asymmetric exponential production curve for most of them (Brandt 2007), with typically a steeper slope prior to the peak than after the peak. In general, an asymmetric approximation of the production curve (eq. 5) yields a more reliable result than a purely symmetric one.

An alternative approach to modelling an asymmetric production curve is a double-sided exponential model in which the paths of increasing and decreasing production are approximated separately by exponential functions. Brandt (2007) showed in an empirical analysis that most crude oil production curves follow an asymmetric model in which the increasing production path typically follows a steeper slope (mean +7.8 %/a) than the decreasing path (mean -2.6 %/a). This model cannot be applied to production curves that are characterised by a plateau but only to those that show a distinct sharp peak.

It is clear from the above that the determination of the timing of the peak production of any commodity requires a reasonable estimate of Q_∞. As mentioned above, Q_∞ can be constrained by applying either the Hubbert Linearisation or the parabola method, provided production data are available for the entire production period. In many cases, especially when production commenced in pre-industrial times, such a complete data set does not exist. For example, gold has been mined for probably more than 7000 years. Yet, annual production records have been kept only from 1851, i.e. the historic production up to 1850 has to remain speculative. Rough estimates of the pre-modern gold production prior to 1851 range from c. 15 000 t (combination of estimates by Soetbeer, 1879, and Bache, 1987) to c. 7 000 t (Goldfarb et al. 2001). Müller

& Frimmel (2011) adapted the parabola method to model historic production of non-renewable resources for those ancient times for which no reliable annual production data are available. They fitted a second-order parabola through the annual production data plotted against cumulated production and extrapolated the parabola to the left. Its intersection with the x-axis where $P = 0$ yields an estimate of early historic production. In the case of global gold production, a pre-1851 production of approximately 10000 t Au could thus be modeled (Fig. 5) – a value that is comfortably close to, i.e. between, the above independent estimates.

The importance of knowing the complete historic production becomes obvious when applying the Hubbert Linearisation to the global gold production data set. If the pre-1851 production is ignored, the intersection of a support line with the x-axis would give a Q_∞ of 280 000 t Au, but if a pre-1851 production of 10 000 t is taken into account, Q_∞ increases substantially to 390 000 t Au (Fig. 6).

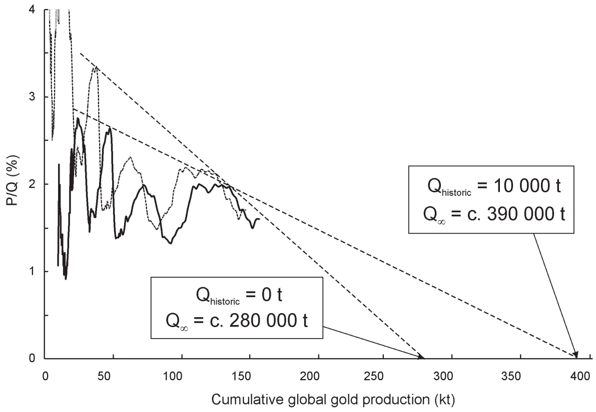

Fig. 6. Application of the Hubbert Linearisation to global gold production: Ratio of annual production (P) over cumulated production up to a given year (Q) as a function of Q; assuming pre-1851 production ($Q_{historic}$) = 0 (dotted line) yields Q_∞ = 280 000 t, whereas $Q_{historic}$ =10000 t (solid line) yields Q_∞ = 390000 t (modified from Müller & Frimmel 2011).

Forward modelling of future production based on historic production data may be meaningful as shown by the above examples. Intuitively the significance of such forecasts is dependent on the overall maturity of the production cycle. High maturity, as for example in the case of the USA crude oil production or the South African gold production, promises more reliable forecasts. In contrast, the global copper production is still at a comparatively immature level. Since 1900 it has been increased exponentially at a rate of approximately 3% per year (Fig. 7a). There is no evidence at all for global Cu production approaching a peak in the foreseeable future. Fitting a second-order polynomial function to the historic production data using the least-squares method yields a Q_∞ that is orders of magnitude higher than current estimates on identified Cu resources, which range from 1.1 Gt (Raw Materials Data base, as per May 2011) to 1.5 Gt (USGS data). This range is slightly lower than the Q_∞ esti-

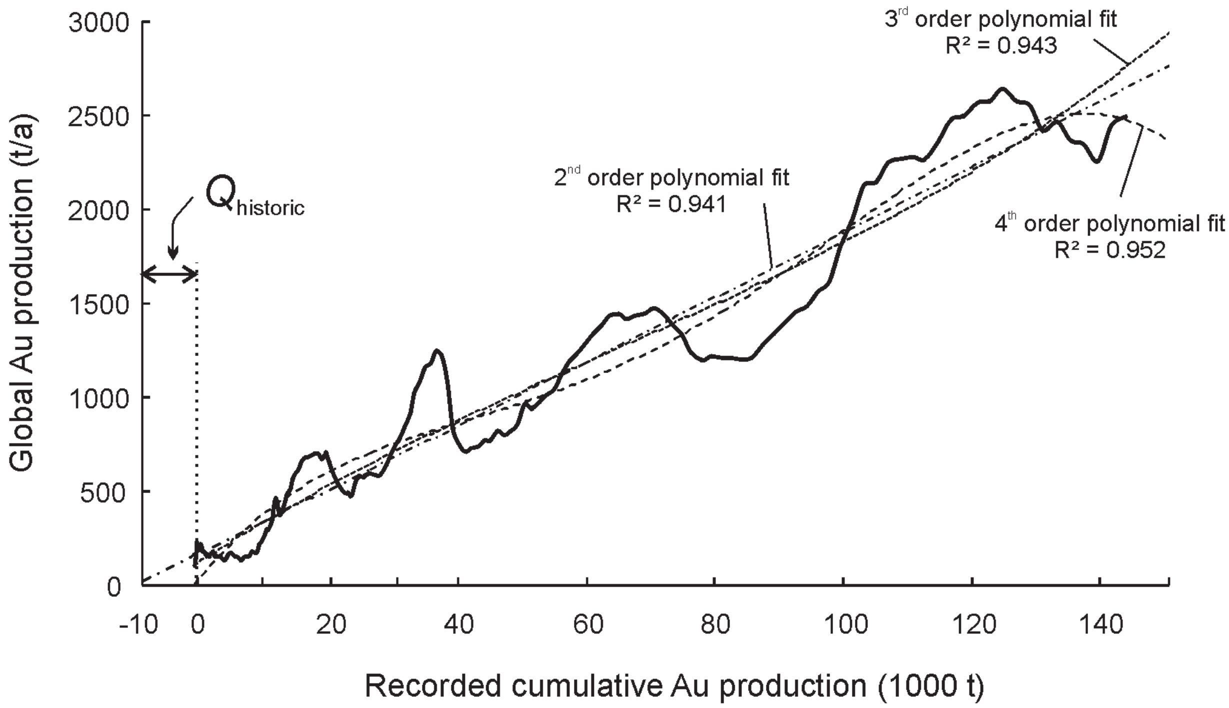

Fig. 5. Global gold production from 1851 to 2009 in terms of annual production P versus cumulated production Q (thick solid line); also shown is the approximation by a second-order and higher order polynomial functions (thin parabola). Extrapolating the second-order polynomial fit back in time leads to an interception with the x-axis at -10000 t which can be regarded as historic Q (modified from Müller & Frimmel 2011).

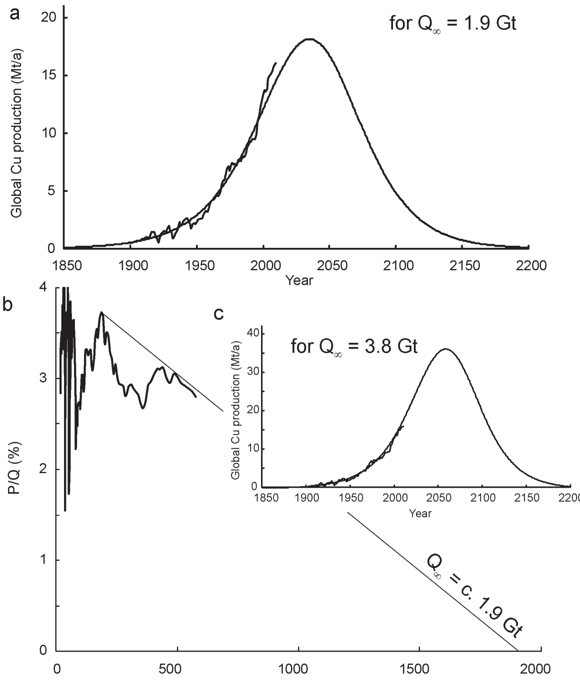

Fig. 7. (a) Global copper production curve for the period 1900 to 2010, approximated by a logistic function, based on a hypothetical Q_∞ of 1.9 Gt Cu as derived from Hubbert-Linearization shown in (b); production data from the USGS, cumulative production prior to 1900 is assumed to be 17 000 kt as obtained through the parabola method of Müller & Frimmel (2011); note the still relatively high P/Q ratio of c. 3 %; (c) Modelling the production curve based on arbitrarily chosen Q_∞ of 3.8 Gt shifts the peak year to 2058, illustrating the dependence of production forecasts on Q_∞.

mate of some ~~2.1~~ Gt obtained by classic Hubbert Linearisation (Fig. 7b). The *P*/*Q* ratio is, however, with close to 3 % still too high and leaves lots of room for considerable variation (most likely increase) in Q_∞. According to the model (Fig. 7a) the production peak would be reached in 2027 with an annual production of slightly above 20 Mt Cu. If the assumed value for Q_∞ is doubled, a vastly different outlook on the future production cycle would emerge (Fig. 7c), which illustrates that no meaningful forecasts can be made without good constraints on Q_∞. This, in turn, is only possible when production has reached an advanced stage and *P*/*Q* is low.

On a global scale, long-term forecasts obtained from the application of sigmoid functions have the advantage that they take into account the possibilities of disruptive factors, such as wars, economic crises, etc., as well as constructive factors, such as new technological advances, global economic boom times, etc., by extrapolating from a past that has been affected by all of these factors into the future.

2.2 Alternative sigmoid functions

While the asymmetric approximation of a given production curve using a general Verhulst Function (eq. 5) presents a notable improvement over a simple symmetric logistic function (eq. 2), it is by no means the only possible approach to modelling a statistic forecast. Other sigmoid functions that could be used, apart from a Gaussian normal distribution and the above Verhulst Function are the Gompertz, Weibull, Richards, and Johnson functions. The density function to describe a Gaussian normal distribution is given by:

$$P(t) = P_{\max} \bullet e^{(-(t-t_0)^2 / 2w^2)} \qquad (6)$$

where to is the shift on the y-axis and *w* the standard deviation. The Gompertz Function takes the form:

$$Q(t) = Q_\infty \bullet \mathrm{e}^{-\mathrm{e}^{-k(t-t\mathrm{peak})}} \qquad (7)$$

The inflection point of this sigmoid function is at 1/e of the saturation value. The Weibull Function has a similar form, i.e.

$$Q(t) = Q_\infty \bullet \left[1 - \mathrm{e}^{\left(-t/\left(t_{\mathrm{peak}}+c\right)\right)^b}\right] \qquad (8)$$

where *b* and *c* are empirical parameters that need to be approximated. This four-parameter equation is asymmetric and very flexible because the inflection point is not fixed on the time axis (Dumur et al. 1990). In the case of the Richards Function (Richards 1959), which has been presented already above (eq. 5), the inflection point is again not constant but depends on the parameters.

The Johnson Function,

$$Q(t) = Q_\infty \bullet \mathrm{e}^{-a/b+t} \qquad (9)$$

reaches the saturation value Q_∞ only very slowly, the slope of the function is steepest at $Q_\infty \bullet e^{-2}$, i.e. at c. 13.5 % of Q_∞, which deviates markedly from the expected peak at around $Q_\infty/2$ and is, therefore, unlikely to describe production curves adequately.

Müller & Dirner (2010) compared these various functions using the South African gold production as an example. The example was chosen because a complete production record is available and because the production peak has long been passed (in 1970), i.e. the South African gold industry has reached a very mature state as elaborated upon above. Their results (Fig. 8) show that a Johnson Function gives no reasonable result, the Gompertz Function cannot describe the descending path of the production curve adequately either, whereas the other functions manage to approximate the actual production curve, especially the post-peak descending part, reasonably well. The best result was obtained with the Richards Function, leading to the lowest RMSD and highest coefficients of determination (Müller & Dirner 2010) though the difference to the result obtained from applying a logistic function is minimal (Fig. 8).

2.3 Testing with higher order polynomial functions

We have seen above that fitting a second-order polynomial fit (parabola method) to a given production curve can give useful insights into the likely future production trends as well as into historic production in the absence of actual production data for the early stages of resource exploitation. A simple mathematical way of testing the reliability of the modelled production curve as obtained from the above functions is to fit the $P = f(Q)$ graphs with higher order polynomial functions (Müller & Frimmel 2011). If the parabola for a third-order, or even a fourth-order, polynomial fit is similar to that for the second-order polynomial function, the result can be trusted with a high degree of confidence. Inversely, if higher order polynomial functions yield significantly different results, the modelled curve based on a second-order polynomial fit should be taken with considerable caution.

In the case of USA's crude oil production, for which an excellent match between actual and modelled production has been shown above (Fig. 3), the second-, third- and fourth-order polynomial fits all yield almost identical parabolas (Müller & Frimmel 2011). For the example of the global gold production it was shown in that study that parabolas obtained from second- and third-order polynomial fits are almost indistinguishable but the fourth-order polynomial fit deviates somewhat (Fig. 5). In contrast, the second-order polynomial fit to the global mercury production differs from third- and fourth-order polynomial fits (Fig. 9), which results from an overall very erratic, irregular production curve. However, Hg serves as possibly one of the best examples of a non-renewable commodity that has been already – on a global scale - almost completely exhausted. The modelled Q_∞ of some 650 000 t Hg, obtained independently by both Hubbert Linearisation and the parabola method (not shown) is almost reached (Fig. 9).

Here we apply this test to a further mineral resource that might have already reached its peak – with far-reaching consequences for mankind, i.e. phosphate. Phosphate rock is the principal source of phosphorous, an element without which life is not possible. Together with N and K, P is a fundamental component of fertilisers and consequently is crucial for supplying food to an ever increasing world population. With much of the world's population depending on high-yield agriculture, requiring artificial fertilisers, the demand for phosphate rock can only increase. Yet, the current production cycle seems to have reached a plateau (Fig. 11). Modelling the historic phosphate rock production using a Richards Function and a Q_∞ value of 10^9t as obtained through Hubbert Linearisation (Fig. 10) gives a hypothetical peak in 1996. The actual maximum in global annual production was reached in 1989 with 162 Mt. Subsequently, the production dropped to 118 Mt in 1993 but has since bounced back to almost peak amounts (161 Mt in 2008), thus pointing to an overall plateau rather than a distinct peak. Our result is far more pessimistic than that by Cordell et al. (2009) who predicted a peak in

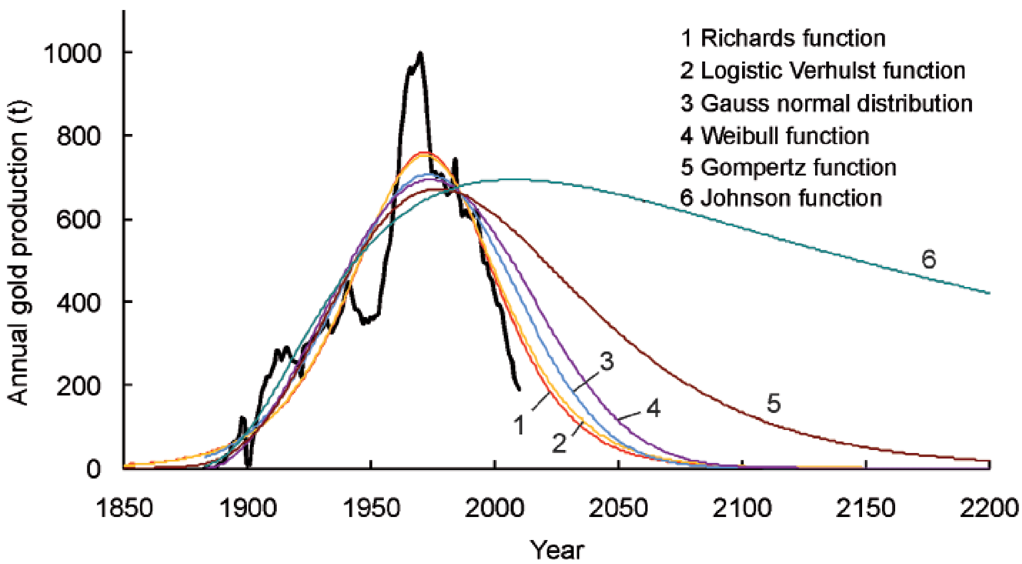

Fig. 8. Comparison of different models to approximate the South African gold production: Gaussian normal distribution, logistic Verhulst Function, Gompertz, Weibull, Richards, and Johnson functions (modified from Müller & Dirner 2010).

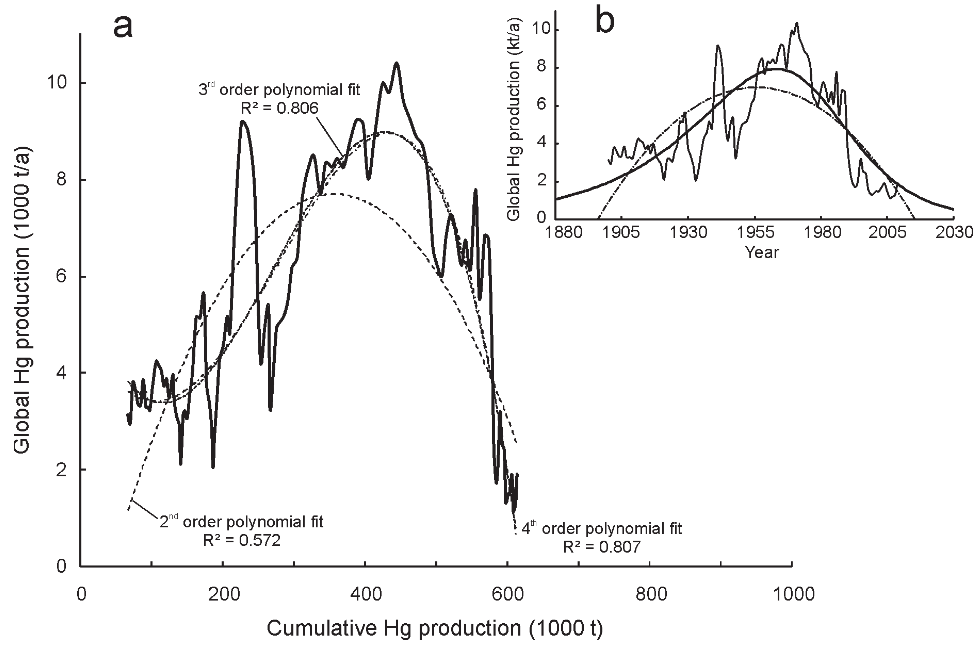

Fig. 9. (a) Application of higher order polynomial functions to global mercury production, on a plot of annual production/cumulative production (P/Q) versus Q (modified after MÜLLER & FRIMMEL 2011); (b) Global Hg production from 1900 to 2009 (data from USGS), 2nd order polynomial fit (stippled parabola) and approximation by a Richards Function (grey curve), modelled on the assumption of Q_∞ = 650 000 t.

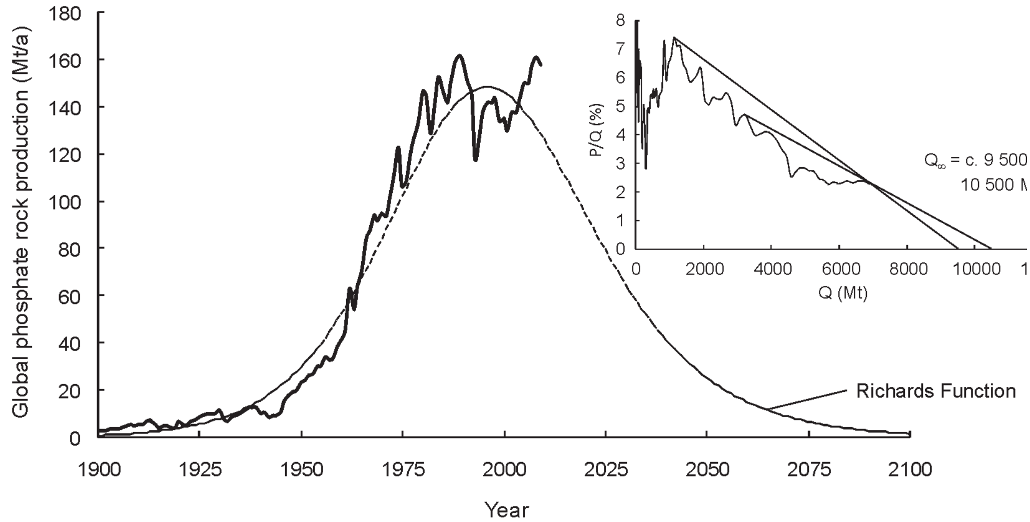

Fig. 10. Global phosphate rock production cycle – real data (from USGS, http://minerals.usgs.gov) and modelled trends, obtained by applying a Richards Function and higher-order polynomial functions, based on Q_∞ derived from trends in the diagram of ratio of annual production (P) over cumulative production (Q) versus Q (insert).

P production to occur at around 2033. The notion that we are currently experiencing a peak (though in the shape of a plateau) in global phosphate production is supported by tests with higher order polynomial functions as shown in Fig. 10. The application of both third- and fourth-order polynomial functions yields similar results all of which point to little potential for significant increases in the future phosphate production. The resulting danger of a growing gap between supply and demand has already led to a steep increase in the price of fertiliser (and consequently that of food), which more than doubled in 2008 relative to the year before and was four times greater than in 2004.

3 Availability estimates based on reserve and resource determinations

3.1 Short- and medium-term forecasts

Day-to-day production of any raw material is driven by well defined reserve estimates. In this context it is necessary to scrutinise the terms resource and reserve as both are defined by different stake-holders in different ways. This inconsistency in the reporting represents a major uncertainty in itself when it comes to estimating future availability of raw materials. In general, “resource” refers to all concentrations of a given naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such a form and amount that profitable extraction of a commodity is currently or potentially feasible. The term “reserve” implies that the material of interest can be extracted and produced at a profit under given market conditions at the time of determination. Depending on the level of probability – and thus on the stage of exploration – resources are typically subdivided (following a recommendation by the USGS) into “inferred”, “indicated” (or “probable”), and “measured” (or “proven”) resources. The latter are a quantity that is computed from dimensions revealed in outcrops, trenches, workings and/or closely spaced drill holes, with grade (quality) computed from analyses done on detailed sampling. The error margin on measured resources should be <20 %. “Indicated resources” are defined by irregular, fairly widely spaced drilling and sampling and have an error margin of 20-40 % (Class I) or 40-70 % (Class II). “Inferred resources” are interpretations based on the expected continuity from known exposures or few irregularly spaced drill holes and are subject to an error margin of 70 – 100 %. Combined measured and indicated resources are also referred to as “demonstrated resources” or, as defined by the International Atomic Energy Association (IAEA), as “reasonably assured resources”. All of the above types of resources combined make up the “identified resources”.

“Undiscovered resources” are, by definition, only postulated and are subdivided into hypothetical and speculative resources. The former are similar to known deposits and may be reasonably expected to exist in the same producing district or region under analogous geologic conditions, whereas the latter may occur either in known types of deposits in favourable geologic settings where mineral/oil/gas discoveries have not been made, or in types of deposits as yet unrecognised for their economic potential.

In exploration, the determination of identified resources typically forms the base for the decision to carry out a pre-feasibility or eventually a feasibility study. Whether an identified resource can be classified as a reserve depends on the production costs, the market situation and the commodity price. Consequently, forecasts based on reserve estimates need to distinguish between different price categories. For example, the IAEA uses four price categories in their outlook on the future of uranium production (OECD/IAEA 2010): considering a current spot market price of around 120 US$/kg U (as per first half of 2011), resources of the two lower price categories, <40 US$/kg U and 40-80 US$/kg U, can be definitely classified as reserves, those of the category 80-130 US$/kg U as marginal, and those of the highest price category of 130-260 US$/kg U as identified resource but not as reserve.

Based on the reserves as reported by mining/oil companies, it should be possible to calculate potential future production with an error margin of <20 %. The actual future production depends, however, not only on the available reserves but also on the production capacity of a mine. Thus, knowing the reserves and the production capacity of the various mines, one can calculate not only a static life span for a given mine but also the availability of a given commodity over a short-term with a high degree of confidence. Longer term forecasts by this way are, however, hampered by the fact that it is not in a company’s interest to convert resources to reserves for more than several years ahead of time.

Medium-term forecasts have to rely, therefore, on resource rather than reserve estimates. This, by definition, increases the uncertainty of such forecasts. Ideally, such medium-term forecasts should be based on measured resources. In reality, the available data base on which to found a medium-term forecast will be, however, a combination of measured and indicated resources, and in many cases even just inferred resources. Undiscovered resources are by definition purely hypothetical and as such must not be considered for any availability forecast. The error margins involved with the different categories of resources (see above) propagates into that of the forecast. Thus, any forecast based purely on inferred resource estimates should be taken with great suspicion, one that is based on undiscovered resources regarded as practically meaningless.

Turning again to the example of the South African gold industry, we recognise that it is unlikely that all identified resources can be converted to reserves. Current reserves for all the South African gold mines amount to 4 346 t Au, total resources to 17 184 t Au (as per May 2011). The amount of Au mined so far (51 553 t Au) plus the known reserves perfectly match the modelled Q_∞ as depicted in Fig. 2 but it also implies that effectively none of the remaining identified resources of 12 837 t Au will ever reach reserve status under current circumstances.

3.2 The example of uranium

A continuing increase in the demand for energy and the desire to reduce the emission of greenhouse gases led to a renewed interest in nuclear energy and plans across the world to build new nuclear power plants. Any expansion of nuclear power capacity is, of course, dependent on the availability of the fuel for these power plants. According to the IAEA close to 14 % of global electricity stems from nuclear power, produced in 440 plants that consume c. 69 kt U/a. The latter amount is more than currently produced by the mining of U-ore, with the difference being covered by U from recycling of old fuel rods and more importantly from nuclear weapons stockpiles following a series of disarmament treaties signed between the USA and Russia since 1987. The amount of U produced from such secondary sources corresponds to 10.6 kt U_3O_8/a (OECD/IAEA 2010). In 2013 the international agreements regarding the supply of U from nuclear weapons will expire, which poses the question of the availability of U from mining in the short- to medium-term. To answer this question we analysed data from a total of 326 U-mines or projects in various stages of development, covering probably >99 % of the current and potential future producers of U from primary resources.

On a global average, reported reserves (as per Oct 2010) would last only for the next six years but, as discussed above, reserves tend to be replenished from year to year as mining companies continue with exploration around operating mines, thus continually converting resources to reserves. It is, therefore, more useful to scrutinise the resource data instead. In all of the currently operating U-mines together, reported inferred, indicated and measured resources of 5381 kt U_3O_8 are contained in a total of 13152 Mt of ore. In addition, seven new mining projects are under construction and they add a total of 482 kt U_3O_8, contained in 118 Mt ore. Twelve projects are at an advanced stage with completed feasibility studies. All of them together contain resources of 259 kt U_3O_8 within 197 Mt ore. Projects for which a pre-feasibility study has been completed total 39 and they contain resources of 1412 U_3O_8 within 5771 Mt ore. A large proportion of these resources represent, however, inferred and indicated but not measured resources. Projects at an early stage of development without a completed pre-feasibility study are numerous. We analysed 170 of them (maybe leaving out some insignificant projects) and all of them together reportedly contain 2840 kt U_3O_8 within 4550 Mt ore. Countries with the largest resources in this kind of projects are South Africa (1316 kt U_3O_8), Russia (445 kt U_3O_8), Australia (284 kt U_3O_8), Canada (200 kt U_3O_8), and USA (166 kt U_3O_8). Most of these projects concern small occurrences with <20 kt U_3O_8. Only 30 of the 170 projects contain >20 kt U_3O_8, and these are mainly in auriferous and uraniferous conglomerates in the Mesoarchaean Witwatersrand Basin (South Africa) and tailings at existing and historic Witwatersrand gold mines, as well as in the Elkon District in Russia where the development of the Elkonskoye deposit is currently the most expensive exploration project of all (estimated project costs of 3.6 billion US$). Thus the total measured, indicated and inferred resources (incl. reserves) amount to some 10.3 Mt U_3O_8. This is considerably higher than the 7.4 Mt reported by OECD/IAEA (2010). The difference can be explained largely by discrepancies in the categorisation of ironoxide-copper-gold (IOCG) deposits, the biggest of which, Olympic Dam (S-Australia), is the world's largest uranium resource (28 % of global resource), but also in the assessment of the tailings of the South African gold mines (943 kt U_3O_8) and that of black shale-hosted U-mineralisation (for a comparison see Table 1).

Taking an optimistic viewpoint and assuming that all of the known resources can eventually be exploited, one can calculate the period for which these resources would last, if the current demand for U remained static, as 141 years. The assumption of future demand remaining at constant levels for decades is, however, as unrealistic as the assumption of a 100% exploitation rate of a given re-

Tab. 1. Global uranium resources (reported as U_3O_8), differentiated according to genetic deposit type, in comparison to data provided by OECD/IAEA (2010).

Genetic type	**U_3O_8 resource (kt)**	**%**	**U_3O_8 resource (kt)**	**%**
	this study		*OECD (2010)*	
Granite-hosted	543,80	5,28	331,7	4,46
Volcanic-hosted	364,90	3,55	344,4	4,63
Porphyry Copper Deposits	117,10	1,14		
IOCG deposits	2906,83	28,24	1480,6	19,91
Unconformity-type	965,16	9,38	865,3	11,63
Sandstone-hosted	2006,32	19,49	1942,9	26,12
Breccia-hosted	1,81	0,02		
Hydrothermal vein-type	180,02	1,75	340,5	4,58
Metasomatite-hosted	864,35	8,40	858,1	11,54
Archaean placer deposits	408,08	3,97	254,6	3,42
Black shale-hosted	606,25	5,89		
Phosphorite	50,00	0,49		
Superficial calcrete	285,77	2,78		
Tailings	946,71	9,20		
Not classified	44,48	0,43	1019,0	13,70
Total	**10291,56**	100,00	**7437,02**	100,00

source. In their latest report OECD/IAEA (2010) predicts a small increase in future U demand over the next five years and thereafter a steeper increase to between 103 and 163 ~~Mt~~ U_3O_8/a by 2035. The latter range is based on two scenarios: a low-case scenario, assuming a conservative expansion of nuclear power capacity by 37 % relative to the reference year 2009, and a high-case scenario that is based on a progressive expansion of worldwide nuclear power capacity by 110 % until 2035. At this stage no meaningful prognosis on nuclear power capacity is possible for the time beyond 2035. Assuming a static development after 2035, the low-case scenario for the time until 2035 would imply that the currently known resources would last for 101 years. For the high-case scenario this time span would decrease to 68 years (as from 2010). The forecasts given by OECD/IAEA (2010), typically the principal source of information for policy-makers on this matter, are similar. They claim that the identified resource base would be sufficient for >115 years of reactor supply (as compared to 141 years in this study) and then go on that the entire resource base, i.e. identified and undiscovered resources, would increase this period to >300 years.

All of these predictions were made prior to the disaster at the Fukushima nuclear power plant in Japan in March 2011, which has radically changed the perception of nuclear energy and its risks. The events in Japan painfully illustrated the strong dependence of future nuclear power utilisation, and thus demand for U, on public opinion, which reflects the problem of effectively unpredictable external costs that are invariably involved with the generation of electricity from nuclear power. Public opinion on this topic has swayed widely over the past three decades, strongly influenced by the memory (and fading thereof) of nuclear catastrophes, such as those in Chernobyl and more recently in Japan. As there is effectively no other peaceful use for the commodity U than generating electricity, the future demand of this commodity will remain most strongly affected by accidents, such as those in Chernobyl or Fukushima, which are not predictable. Consequently, the medium- to long-term demand for U is extremely difficult to quantify.

Irrespective of the problems in predicting the future demand for U, the seemingly very comforting time spans of >100 years, or even >300 years, of future U supply as given above are purely hypothetical and effectively meaningless. The undiscovered resources, as already pointed out, cannot be used for predictions of availability. And by far not all of the identified resources can be regarded as being potentially available for mining. To come up with a more meaningful estimate on potentially available resources, we analysed the predicted life spans of existing mines and concrete planned future mine projects. The life span of a mine is calculated from the demonstrated resource base (in the case of longer-term forecasts also the identified resource base) divided by the actual or planned annual production capacity of the (planned) mine.

The life spans of existing mines can be estimated with a comparatively high degree of confidence. Only those producers that individually contribute >2 % of the global production are considered here in more detail. In 2009 their combined production made up 79 % of the global production. Forecasts of future productions until 2035 were derived from reserve and resource data as well as mine capacities reported by these mines for 2009 (Tab. 2). It is obvious from that table that Olympic Dam will be by far the largest producer in the future. The given numbers are based on the assumption that a very ambitious expansion project, planned for the next 11 years, will be carried out. In that case the operating company, BHP Billiton, plans to increase the production of U_3O_8 from currently 4 to 19 kt/a. The total future production from existing mines, as given in Tab. 2, takes into account only the top 17 mines and thus, by analogy with the above proportion should only represent approximately 79 % of future production. However, mines rarely manage to exploit 100 % of their resources (and eventually reserves) but roughly 80 % is probably a realistic average. Consequently, the total future production as given in Tab. 2 should be close to what is achievable under realistic conditions.

More difficult is the assessment of future production from projects that have not yet turned into operating mines. Nevertheless, potential future production, based on resource estimates and expected life-of-mine data (and/or information on planned production capacity) provided by the project owners, has been calculated (Tab. 3). Naturally, the most reliable predictions can be achieved from projects at a very advanced stage of development, i.e. those that are under construction or with a completed feasibility study. Most speculative are predictions on the availability of U from those resources that have not even undergone a pre-feasibility study. Considering that the time span that elapses from the date of discovery to the completion of a mine is in the range of 10-15 years under ideal circumstances and in most cases considerably longer, no significant contribution to the global production is expected to come from these projects in the short- to medium-term. Moreover, most of these conceptual projects without pre-feasibility study are relatively small with identified resources of <20 kt U_3O_8 (Fig. 11). They are unlikely to ever become major role players in the global arena. An exception is the Elkon District in Russia, where huge resources (foremost the Elkonskoye deposit) wait to be mined with a planned production of 5 kt U/a from 2024 (www.elkon.armz.ru), and the surficial Yeelirrie Deposit in Australia, where a production of 5 kt

Tab. 2. Production forecasts for the top 17 uranium mines until 2035 (in 1000 t U_3O_8)

Rank	Name of mine	Method*	Production (kt U3O8) in 2009	Proportion of global production (%)	Life of mine (years)	Projected annual production (kt U)	Available U3O8 (kt)				
							2010-2014	2015-2019	2020-2024	2025-2029	2030-2035
1	McArthur River & Key Lake	UG	8,640	14,95	19	8,8	51,9	51,9	51,9	31,1	0,0
2	Ranger Uranium Mine	OP	5,220	9,03	15	5,5	32,4	32,4	25,9	0,0	0,0
3	Rössing Uranium Mine	OP	4,151	7,18	14	4,0	23,6	23,6	14,2	0,0	0,0
4	Krasnokamensk Mill Uranium Mines	UG	3,542	6,13	38	3,1	18,3	18,3	18,3	18,3	21,9
5	Olympic Dam Copper/Gold Mine	UG	3,520	6,09	20+	4,0	23,6	23,6	112,0	112,0	134,4
6	Tortkuduk Uranium Mine	ISL	2,680	4,64	11	1,0	5,9	5,9	0,0	0,0	0,0
7	Navoi Mining & Metallurgical Combine	ISL	2,77	4,79	20+	2,0	11,8	11,8	11,8	11,8	14,2
8	Arlit Uranium Mine	OP	2,132	3,69	20+	1,1	6,5	6,5	6,5	6,5	7,8
9	Rabbit Lake Uranium Mine	UG	1,700	2,94	6	4,6	27,1	5,4	0,0	0,0	0,0
10	Akouta Uranium Mine	UG	1,692	2,93	11	2,5	14,7	14,7	2,9	0,0	0,0
11	Budenovskoye-2 Uranium Mine	ISL	1,669	2,89		1,2	7,1	7,1	7,1	0,0	0,0
12	McClean Lake Uranium Mine	OP	1,390	2,41	0	0,0	0,0	0,0	0,0	0,0	0,0
13	Langer Heinrich Uranium Mine	OP	1,430	2,47	15	2,4	14,2	14,2	14,2	0,0	0,0
14	Moinkum Yuzhny Area Uranium Mine	ISL	1,300	2,25	20+	1,0	5,9	5,9	5,9	5,9	5,9
15	Akdala Uranium Mine	ISL	1,225	2,12		1,2	7,1	7,1	0,0	0,0	0,0
16	Yuzhny Karamurun Uranium Mine	ISL	1,190	2,06	20+	0,5	2,9	2,9	2,9	2,9	3,5
17	Mynkuduk East	ISL	1,180	2,04	20+	0,3	1,8	1,8	1,8	1,8	2,1
upcoming in the future											
	Inkai Uranium Deposit	ISL	0,840	1,45	20+	2,7	15,9	15,9	15,9	15,9	19,1
	Budenovskoye Uranium Mine	ISL	0,460	0,80	?	3,0	0,0	17,7	17,7	0,0	0,0
	Total			78,62		48,9	270,6	266,6	309,0	206,3	209,0

* ISL - in situ leaching, OP - open pit, UG - underground

Tab. 3. The most important projects (grouped according to stage of development) that might contribute to the future uranium production.

Rank	Name of mine	Method*	Resource (kt U3O8)	Project start date (year)	Expected annual production (kt U/a)	Available U3O8 (kt)				
						2010-2014	2015-2019	2020-2024	2025-2029	2030-2035
Mines under construction										
1	Jabiluka (North Ranger) Uranium Mine	UG	195,570	?		0,0	0,0	0,0	0,0	0,0
2	Cigar Lake Uranium Mine	UG	159,344	2014	5,8	6,8	34,2	34,2	27,4	0,0
3	Novokonstantinovskaya Uranium Mine	UG	110,418	2015	2,5	0,0	14,7	14,7	14,7	14,7
4	Ezulwini Mine	UG	112,261	2019	1,2	0,0	1,4	7,1	7,1	7,1
5	Mynkuduk Central	ISL	88,500	2011	2	9,4	11,8	11,8	11,8	11,8
6	Mynkuduk West	ISL	44,250	2011	1	4,7	5,9	5,9	5,9	5,9
7	Kharasan 1&2	ISL	10,290	2012	2	4,7	7,1	0,0	0,0	0,0
Projects with completed "feasibility study"										
1	Imouraren Uranium Deposit	ISL	125,950	2014	5	5,9	29,5	29,5	29,5	29,5
2	Four Mile Uranium Deposit	ISL	32,340	2011	0.68/2.045	2,4	12,1	12,1	7,2	0,0
3	Dornod Uranium Project		30,322	2012	1,15	2,7	6,8	6,8	5,4	0,0
4	Bakouma Uranium Deposit		15,907	?	?	0,0	0,0	0,0	0,0	0,0
5	Roco Honda Uranium Deposit	ISL	15,100	?	?	0,0	0,0	0,0	0,0	0,0
6	Koongarra Gold/Uranium Mine	OP	14,220	?	?	0,0	0,0	0,0	0,0	0,0
Projects with completed "pre-feasibility study"										
1	Viken Uranium Deposit	OP	485,242	?	?	0,0	0,0	0,0	0,0	0,0
2	Rössing South Uranium Deposit	OP	164,925	2015	4,5	0,0	26,5	26,5	21,2	0,0
3	Kvanefjeld Uranium/REE Deposit	OP	127,96	2016+	3,9	0,0	18,4	23,0	23,0	23,0
4	Etango Uranium Deposit	OP	96,5458	2014+	2	0,0	11,8	11,8	11,8	4,7
5	Severinskoye Uranium Deposit		58,800	?	?	0,0	0,0	0,0	0,0	0,0
6	Trekkopje Uranium Deposit	OP	50,946	2012	3	10,6	17,7	14,2	0,0	0,0
7	Michelin Uranium Deposit	OP,UG	47,213	?	2,5	0,0	0,0	14,7	14,7	14,7
8	Yuzhnaya/Elkon Uranium Deposit		44,250	2015	1	0,0	5,9	5,9	5,9	5,9
9	Letlhakane Uranium Deposit		44,800	?	?					
10	Valencia Uranium Deposit		31,911	2015e	1	0,0	5,9	5,9	5,9	2,4
11	Mkuju River Uranium Deposit		37,904	2011	1,4	6,6	8,3	5,0	0,0	0,0
12	Semizbai Uranium Deposit	ISL	20,650	2012	0,5	1,8	2,9	2,9	2,9	2,9
Conceputalised projects										
1	Elkonskoye Uranium Deposit		369,964	2024	5	0,0	0,0	11,8	14,7	14,7
2	Itataia Uranium Deposit	OP	67,239	2013	1	2,4	5,9	5,9	5,9	5,9
3	Yeelirrie Uranium Deposit		52,500	2014+	5	0,0	29,5	29,5	0,0	0,0
4	Midwest Uranium Deposit	UG	29,922	2013	2,3	5,4	13,6	13,6	8,1	0,0
5	Olovskoye Uranium Deposit	OP,UG	20,650	2014	0,6	0,0	3,5	3,5	3,5	3,5
	Total		***2705,894***			**58,1**	**256,2**	**279,1**	**215,1**	**143,3**

* ISL - in situ leaching, OP - open pit, UG - underground

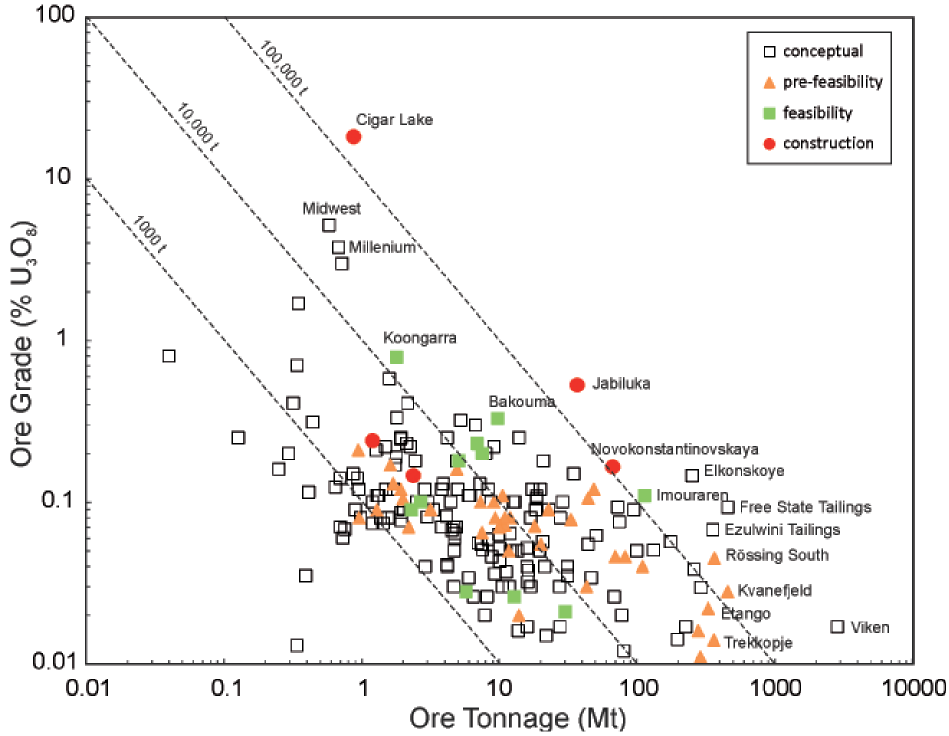

Fig. 11. Uranium ore grade versus tonnage diagram for current projects, grouped according to stage of project development. Note that most of the occurrences under investigation contain resources of <10 kt U_3O_8.

U/a over a period of 10 years is feasible from 2015 at the earliest (www.aph.gov.au/library/pubs/bn/sci/UraniumWA.htm).

If all of the current U-projects came to fruition as planned, operating at full capacity, the temporal evolution of the predicted available amount of U would be as shown in Fig. 12. There the 25-year forecast in supply is compared with the low- and high-case scenarios of OECD/IAEA (2010). The current gap between demand and supply from primary U resources will close rapidly and from 2014 the demand will be met completely by U from mining. If all of the short-term projects were actually realised, the annual U production would be considerably higher than the forecasted demand. Between 2015 and 2019 this overcapacity would be between 22 and 31 kt U_3O_8/a, depending whether the low-case or the high-case scenario is used. If the expansion plans for Olympic Dam are not accomplished, the overcapacity would be reduced by 15 kt U_3O_8/a after 2020 (stippled line in Fig. 12).

After 2025 the predicted situation changes drastically. The U supply from mining will decrease to amounts that could meet the prognosticated demand for the low-case scenario until 2027, but would fall short by 22 kt/a in the high-case scenario. Thereafter the gap between supply and demand will open up further and by 2035 a short-fall between 31 and 91 kt/a is predicted for the low- and high-case scenarios, respectively. Without the Olympic Dam expansion, this deficit would be as much as 46 to 106 kt/a.

Independently of any actual data on available resources, planned projects and anticipated production capacities, the future production from uranium mines was also modelled following the methods outlined in Section 2. The *P*/*Q* ratio is with about 2 % still fairly high, which makes it impossible to obtain a reliable estimate on Q_∞ by Hubbert Linearisation. Close to 3.0 Mt of U_3O_8 has been produced so far by mining. Adding to this the currently known resources of 10.3 Mt gives a so far geologically constrained Q_∞ of 13.3 Mt. Based on this amount, hypothetical production curves were modelled using various sigmoid functions (not shown). Applying the Richards Function, for example, yields a maximum production in the mid-2020s with a peak of 183 kt U_3O_8 in 2026. This peak production is much higher than the one shown in Fig. 12, because by far not all of the identified resources will gain reserve status.

A supply curve as shown in Fig. 12 would defeat, of course, any market economic sense. The hypothetical overcapacity in the years 2015 to 2024 would invariably depress the price for U and would lead to a delay in the realisation of a number of projects. Thus some resources will be saved for later and can then be used to offset the predicted deficit after 2028. In the case of OECD/IAEA's (2010) low-case scenario, the surplus in the period from 2015 to 2024 would cover the hypothetical deficit in the years 2028 to 2035. For the high-case scenario, the predicted surplus in the period 2014 to 2023, totalling 171 kt U_3O_8 would not suffice to cover the modelled deficit from 2025 to 2035, which amounts to 677 kt U_3O_8.

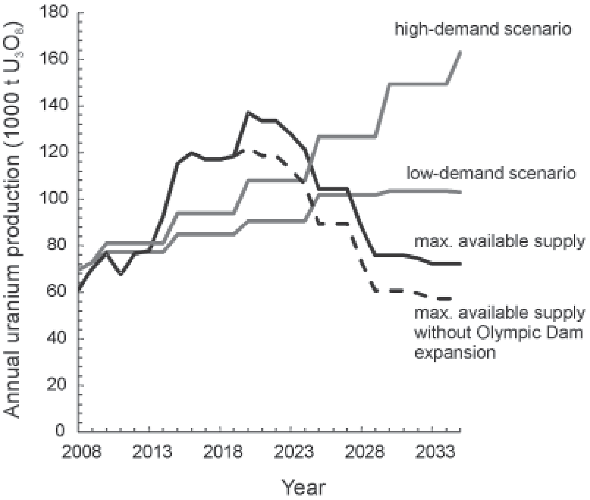

Fig. 12. Forecast until 2035 of maximal available U from mining compared with low- and high-case demand scenarios (in 5-year steps) as predicted by OECD/IAEA (2010)

The predicted net deficit for the high-case scenario could be in parts reduced if the Jabiluka Deposit in northern Australia can be mined. Currently, this deposit, which contains a resource of some 196 kt U3O8, is put on hold for socio-political reasons. The current owner, Rio Tinto, intends to bring Jabiluka into production once the nearby Ranger deposit is exhausted (projected for 2023). This could add c. 5 to 6 kt U_3O_8/a (if one includes the similar Koongarra project) to the global production. Further potential lies in the Elkon District, where only about 41 of the overall resource of 370 kt U_3O_8 would have been mined by 2035. There the limiting factor is production capacity, designed to be 5 kt U/a. All in all some extra 15 kt U/a could be possible for the period 2030 to 2035. This would still leave a deficit of 70 to 80 kt U_3O_8/a from 2030.

Such a deficit as projected for the high-case scenario would invariably lead to a price increase, which in turn could move several resources into the reserve category. This raises the question whether a decreasing supply/demand ratio and consequently higher prices will not only intensify exploration but also result in a corresponding increase in new discoveries and in the overall reserve base. Although such a direct relationship between increase in the commodity's price, exploration expenditure and new discoveries that can expand the reserve base is a very common perception, it does not hold up to scrutiny as elaborated upon in the next section.

4 The likelihood of finding new deposits

Taking for example the average Au concentration in the continental crust, i.e. 1.5 µg kg^{-1}, and a total continental crustal mass of 2.97×10^{19} t, a total of some 45 Gt Au should be present therein (Frimmel 2008). This is an exorbitant amount in comparison to the total amount of gold that has been mined to date, i.e., c. 157 000 t Au (data from the Raw Materials Group, USGS, South African Chamber of Mines, and Müller & Frimmel 2011). Even if only the top 4 km of the crust, i.e. about the maximum possible depth of underground mining operations, are considered as well as all the known gold resources and reserves, the amount of Au in ore deposits would be no more than 7 x 10^{-7} of all the Au theoretically present in the crust (Frimmel 2008). The very low solubility of Au in most geologic fluids or melts made it effectively impossible to concentrate a larger proportion of crustal Au into ore bodies. Nevertheless, one could draw the conclusion from this extremely small proportion that to date only a small part of the theoretically available gold deposits have been discovered and huge treasures are still hidden underground. If that were the case, more exploration, driven by higher prices, should result in correspondingly more new discoveries. Similar thoughts could be applied to most other metallic mineral resources and, if correct, it should be possible to replenish all those resources that are currently being mined – thus invalidating the Hubbert model.

A number of institutions have been arguing along the above lines against a Hubbert model. For example, the World Nuclear Association stated in a recent report (WNA 2010) that "a doubling of price from present levels could be expected to create about a tenfold increase in measured economic resources, over time, due both to increased exploration and the reclassification of resources regarding what is economically recoverable". Unfortunately, such an optimistic outlook is not supported at all by actual data. The historically by far single most important gold-producing nation, South Africa, has reached its peak production as early as 1970 (Fig. 9), a decade before the gold price reached its first peak (Fig. 13a)! Since then, the increase in the gold price failed to push up the output of this largest of all gold producers, which has been declining at a rapid rate in spite of record highs in the gold price.

There is no other non-ferrous metal for which as much exploration money has been and is being spent as gold. On a global scale, gold exploration expenditure shows no correlation whatsoever with the amount of new discoveries (Fig. 13b). As can be seen on that figure, most discoveries were made in the 1950s and 1960s – long before the gold price began to soar after the termination of the Bretton-Woods agreement in 1971. Exploration expenditure was minimal in those early days. Between 1950 and 1972 the average amount of newly discovered gold per year was almost 70 % higher than annual production. With the sharp increase in the gold price in 1980, exploration efforts increased markedly, surpassing 4 billion US$ in the late 1980s as opposed to amounts of around 0.2 billion US$ prior to the 1980s (Fig. 13). This first wave of exploration hype led to another peak in discoveries but not at a proportion that would correspond to the increase in exploration expenditure. Since then exploration budgets followed cycles that mirror those in the world economy. Further peaks in exploration expenditure were, however, not rewarded with corresponding peaks in new discoveries – a phenomenon that proved to be independent of a soaring gold price (compare Figs. 13a and 13b).

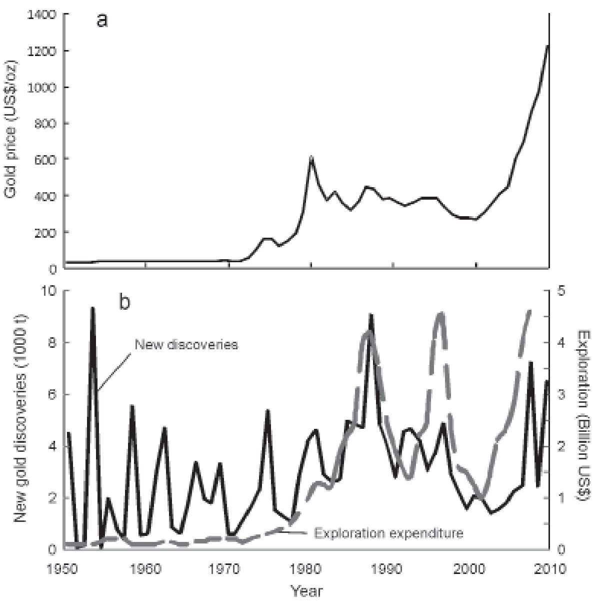

Fig. 13. (a) Variation in gold price (in US$) between 1950 and 2010; (b) new discoveries of gold deposits (black line) compared with exploration expenditure (grey line) over the same period (modified after Mc Keith et al. 2010 and supplemented with USGS data for the most recent years).

As pointed out by Mc Keith et al. (2010), the return for every dollar spent on gold exploration has continuously decreased over the last five decades. The ratio of newly discovered gold divided by exploration costs averaged over a decade has followed a downward trend from 105 (expressed in US$) in the 1960s to a mere 11 in the 2000s (Fig. 14). Exploration is by far not as successful anymore as it used to be half a century ago in spite of a commodity price that has never been as high. The downward trend in the success of exploration is also reflected by the quality of the new discoveries. The average ore grade in the main gold-producing countries of the last century (South Africa, Australia, Canada, Brasil and USA) dropped continually from close to 20 g Au/t at the turn of the 20th century to 8 g/t in 1950, 2.3 g/t in 1980 and 1.1 g/t in 2007 (Müller & Frimmel 2010).

Falling ore grade is typically compensated for by an increase in the amount of ore processed but

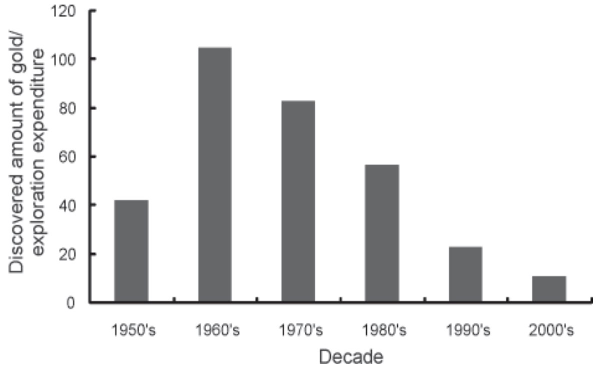

Fig. 14. Decade-averaged ratio of the value of new gold discovered over exploration expenditure (in US$) from the 1950s to the 2000s (modified from Mc Keith et al. 2010).

there are limits. This is particularly well illustrated by the example of the very mature South African gold mining industry (Fig. 15).

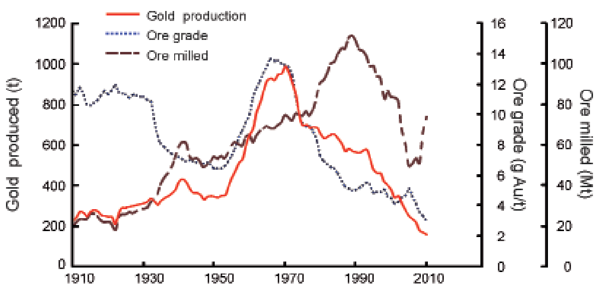

Fig. 15. History of annual South African gold production, ore milled, and gold grade from 1910 to 2010 (data from South African Chamber of Mines, www. bullion.org.za); note that almost all of that production comes from the Witwatersrand goldfields.

Hartnady (2009) distinguished between three stages of gold production in South Africa. An early stage (from discovery in the 1880s until 1951) was characterised by fluctuating production, with several downturns due to wars and unrest, but a general trend towards higher production with time. At the same time the ore grade decreased continually once the rich, easily accessible zones had been exploited. The drop in ore grade from around 11 to 7 g/t in the 1930s and 1940s was made up for by a drastically increased tonnage of ore milled. Thus the gold output could be increased in spite of lower grades. From 1952 to 1965 followed the transition stage that was marked by a steep increase in ore grade. This sudden change in the trend of the ore grade was largely due to the introduction of new technology that made it possible to mine at deeper and deeper levels. In combination with continually increasing tonnage of ore processed it led to a steep increase in the gold production. The third, late stage from 1966 to the present has been marked by a similarly steep decline in ore grade from 13.7 g/t to currently 3.0 g/t. Initially, this reversal could be combated by further increase in the amount of ore milled until the gold production peaked in 1970 with 1000.4 t. Since then, even a further increase in tonnage of ore processed could not stop the downward trend in gold production, though it could slow down the decline for some years in the 1980s and 1990s. Most importantly, the limits of increasing ore tonnage have been reached in 1990 when a maximum of 129.4 Mt of ore were processed. Since then, not only ore grade has decreased but also the tonnage of ore milled (Fig. 15). No further technological advance has been able to stop that trend. Although the tonnage of ore milled has recovered slightly in the last two years, this made up only for a particularly poor performance in the mid-2000s. Thus, overall the example of the South African gold mining industry illustrates that in the long run a decline in ore grade cannot be compensated by increasing the tonnage of ore milled.

Similarly to gold, only a poor correlation between exploration expenditure and new discoveries can be established for uranium (Fig. 16).

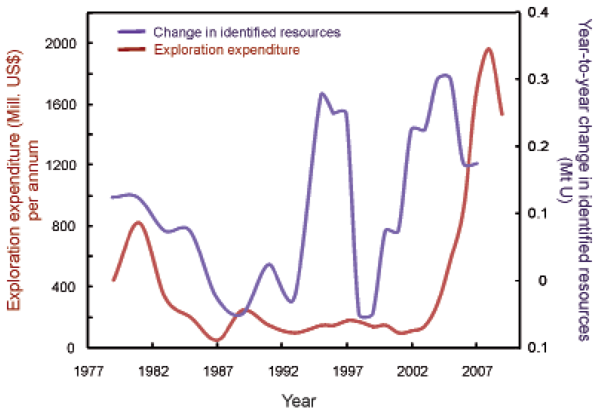

Fig. 16. Expenditure for uranium exploration compared with year-to-year change in identified uranium resources from 1979 to 2009; data extracted from OECD/IAEA (2010).

An early peak in exploration around 1980 and subsequent decrease is somewhat mirrored by new discoveries made at that time. From the 1990s onwards there is, however, no correlation at all. The most recent surge in uranium exploration since 2004 has not been rewarded (yet) with a substantial increase in new discoveries – quite to the contrary (Fig. 16). Trends in exploration expenditure for other metallic mineral resources are very akin to those depicted here for gold and uranium: stagnant for most of the late 1980s and 1990s except for a minor peak in 1997, when total worldwide exploration budgets (excluding uranium) rose to over 5 billion US$ from a background value of around 2 billion US$, they dramatically increased from 2004 to over 13 billion US$ in 2008 (Goulden 2009), though without a corresponding success rate in new discoveries. Similarly, there is no correlation between the price for crude oil, which theoretically should dictate exploration efforts, and the identified resources (Fig. 17).

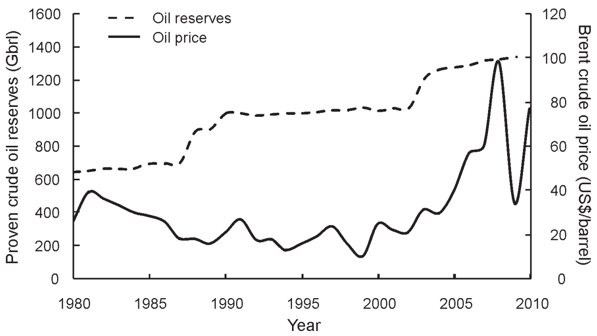

Fig. 17. Change in oil price (brent crude oil in US$/barrel) as compared to change in proven oil reserves for the period 1980 to 2009 (data from U.S. Energy Information Agency, www.eia.gov).

All of the above examples show that it would be a fallacy to believe that any increase in a commodity's price and, in turn, in the amount of money invested into the exploration for that commodity would necessarily result in an ever-growing reserve base. Nevertheless, even if the current success rate in exploration is not as high as one would expect and hope for, it might appear arrogant to assume that future generations of geologists will not be able to make new major discoveries. For example, the discovery of two or three new deposits of the size of Olympic Dam would change the outlook on future availability of uranium, copper and gold quite drastically.

To assess the likelihood of such new discoveries, it might be useful to reflect on the history of the exploration industry in general. This evolution can be subdivided into three principal stages:

(i) In a first stage exploration is conducted mainly by prospecting on the Earth's surface without detailed geological knowledge. Ore bodies that have an obvious surface expression are discovered, the technological effort involved and overall exploration costs are low, and the discovered ore bodies tend to be of high grade. The first stage of gold mining in the Witwatersrand of South Africa (Fig. 15) would be a good example, or the discovery of the high-grade uranium deposits near the margin of the Palaeoproterozoic Athabasca Basin in Canada (e.g. Key Lake deposit) in the 1960s and 1970s. By now most regions of the world have been mapped to such an extent that new discoveries of this nature have become rather unlikely.

(ii) The second stage in exploration history is based on geological models. Intensive research leads to a substantially improved understanding of the geological processes that have been responsible for different styles and types of mineralisation.

With such an understanding, certain geological domains that hold promise of high mineralisation potential can be delineated and exploration can focus on specific target areas. In the Athabasca Basin, for example, this stage led to the discovery of hidden ore bodies that are located beneath hundreds of metres of cover rocks in the centre of the basin, such as the giant McArthur River and Cigar Lake uranium deposits.

(iii) Once the model-based exploration reaches a certain saturation level and new deposits cannot be found any more at the established rate, the exploration industry undergoes a paradigm shift. Completely new ideas and concepts are being sought, with regard not only to the understanding of geological processes but also to new developments in minerals processing or oil/gas extraction that would fundamentally improve the efficiency in the production of a given commodity. For most metallic mineral deposits as well as fossil energy resources, we believe that this third stage has been reached.

Such new developments often revolve around processing of very low-grade ore that would not have been economic in the past. For example, only thanks to the development of the in-situ leaching (ISL) method did the mining of many low-grade sandstone-hosted U-deposits become economically viable. The world's top U-producing country, Kazaksthan, would not play any significant role in the U-industry had it not been for the ISL method. A similar example is the extraction of gas from carbonaceous shale by hydraulic fracturing ("fracking") thanks to new developments in directional drilling. Large-scale leaching by hydrothermal solutions could be the answer to mining gold in the Witwatersrand at depths that are beyond the capabilities of traditional mining methods. Biomining, though in practice already for a number of years, still holds promise to turn many more currently uneconomic occurrences into money-spinning mines. All of these potential future developments have one aspect in common: they apply to deposits of low to very low grade. Most forms of mining require energy and water. The amounts required depend on ore grade. Several recent studies have shown that the amount of energy needed increases exponentially with decreasing ore grade (Mudd 2007, Storm Van Leeuwen 2008, Norgate & Jahanshani 2010; Mudd & Diesendorff 2010). Considering the current uncertainties around the future supply with energy and likely above-inflation increase in energy costs, the long-term availability of mineral resources has to be intimately linked with the development of energy costs and availability.

5 Additional uncertainties in production forecasts

5.1 Production as by-product

A number of commodities are not necessarily produced as main products of mining but as by-products. Some of them are exclusively produced as by-product, such as rhenium (recovered from Mo-deposits), gallium (associated with bauxite, the principal Al-ore), germanium (by-product of Zn production), indium (from Zn-Cu deposits), and rhodium as well as ruthenium (both only with platinum-group metals, PGM). Others are produced as main product in some mines and as by-product in others. The enormous significance of Olympic Dam, where Cu is produced as the main metal, for the future supply of U has already been commented upon above. The production of U as by-product of phosphate mining has been hailed by the OECD/IAEA (2010) as possible answer to long-term shortages of U. Economic extraction of U from phosphate rocks is expensive and would require at least a doubling of current spot market prices for U. Most of the resources are in Upper Cretaceous sedimentary deposits in North Africa (Morocco, Tunisia, Egypt, Jordan, Syria) and Mexico, but they are of very low grade and resource estimates have been downgraded over the past years. Considering the rather modest outlook on the future of phosphate rock production discussed above (see Fig. 10) and the available resource estimates (OECD/IAEA 2010), a major contribution from phosphate mining to the future global U supply is improbable.

More and more gold is recovered as a by-product, mainly from porphyry Cu deposits but also, to a lesser extent, from IOCG deposits. Over the past three decades the contribution of porphyry Cu deposits to the global gold production has risen steadily from 3 to almost 10 % (Scherer 2010). By analogy with the anticipated further exponential growth of global Cu production (Fig. 7) and in the wake of global gold mines having potentially reached their peak already, a progressively larger proportion of the globally produced Au is forecast to come from porphyry Cu deposits. This could be as much as 1000 t/a by 2030 and could help considerably in offsetting the anticipated decrease in Au-output from principal gold mines. For many other commodities that are produced partly or entirely as by-products, production forecasts are not as straightforward because of the additional dependence on production forecasts for the main commodity, which can be highly speculative.

5.2 Monopoly structures

All of the above methods to estimate future production trends assume that free market economic forces dictate the prices of commodities which, in turn, determine the conversion of given resources to reserves. The actual availability is, however, also dependent on the extent to which a potential producer releases material into the world market. Individual national governments are unlikely to exert great influence on global availability of a given commodity if that commodity is produced by many different companies in many different parts of the world as is the case, for example, with Au, Ag and base metals. Difficult to prognosticate problems arise, however, if global production is controlled by only very few companies and/or countries. Then the global supply can be severely reduced or even interrupted by short-term political developments or whatever crisis in the producing country or the producing company.

For instance, in the past the recently much-talked-about rare earth elements (REE) have been extracted from only very few localities. Since 2001 China has produced more than 90 % of REE worldwide. Prior to that, the Mountain Pass deposit in California dominated global REE production for many years (almost all REE, especially light REE, produced between 1965 and the early 1980s came from that deposit). The current monopoly is already being used by China to exert control on the flow of REE into the rest of the world. Export duties and restrictions can lead to serious shortages in the supply outside China, where REE are essential raw materials for modern and future high-tech industries. Theoretically, there should be no shortage of REE in the decades to come. Production data to date show all the hallmarks of a very immature exploitation stage: an exponential growth at 5.4 %/a and a *P*/*Q* ratio that has not commenced a linear trend yet but is fluctuating between 5 and 7 % (Fig. 18),

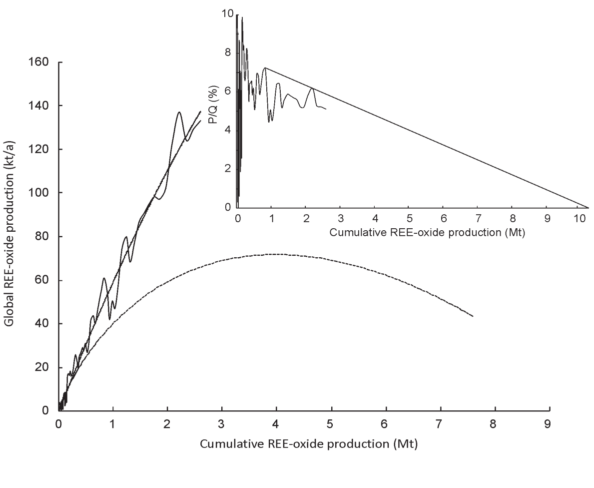

Fig. 18. Global annual rare earth element oxide production as a function of cumulative production (data from USGS); also shown is the annual production/cumulative production ratio (P/Q, insert), which is still too high to yield a meaningful estimate on Q_∞ through Hubbert Linearisation.

which is far too high to obtain a meaningful estimate on Q_∞ through Hubbert Linearisation. The parabola method fails to yield a meaningful result too (Fig. 18), with no peak in REE production in sight. Thus, from a purely production-statistical point, there should be great potential for the delineation of new reserves. It can be expected that any attempt by China to misuse its current de facto monopoly on REE will lead to increased exploration efforts elsewhere and new REE mines to be established. This might include the re-opening of the Mountain Pass mine in the USA. Consequently, in the medium- to long-term, we do not foresee a shortage of REE on the world market, even if some of the REE will see a continuation of the recent surge in demand.

6 Moving towards real costs of mining

Even in the heydays of mining of rich, high-grade deposits, the production costs were unlikely to mirror the actual costs of producing a given commodity. In the past a lack of environmental awareness and/or responsibility, for instance, led in many places to a legacy of contaminated or strongly degraded landscapes once mining had ceased. This not only caused a heavy burden on local communities and governments but also contributed to an overall poor image of mining in the general public. Over the past three decades, the goalposts have shifted considerably in this regard. Following modern environmental regulation and community expectations, at least in the developed countries, rehabilitation after mine closure is now a generally accepted requirement. Still, not all costs of mining are born by the producers. From time to time, when larger accidents happen, the general public becomes aware of the problem of internal versus external costs of mining and power generation. Very sad but prime examples are the recent tragic events around the oil spill following the sinking of the Deepwater Horizon platform in the Gulf of Mexico in 2010 and the enormous contamination with radioactivity following the melt-down of the Fukushima nuclear reactors in tsunami-stricken Japan in 2011. However, even without headline-earning catastrophes, the official production costs in normal day-to-day operations, as reported by mining companies, have been, and still are, unlikely to reflect the true costs of these operations. Some workers have even argued that, for instance, gold mining would not yield a net profit if all costs were considered (e.g. Ali 2006, Whitmore 2006). As shown in Fig. 19 the median production costs increased steadily from 2002 to 2010 – in line with an increase in the gold price. Also shown are the maximum production costs reported, which are far above the contemporary gold price. Not surprisingly, those

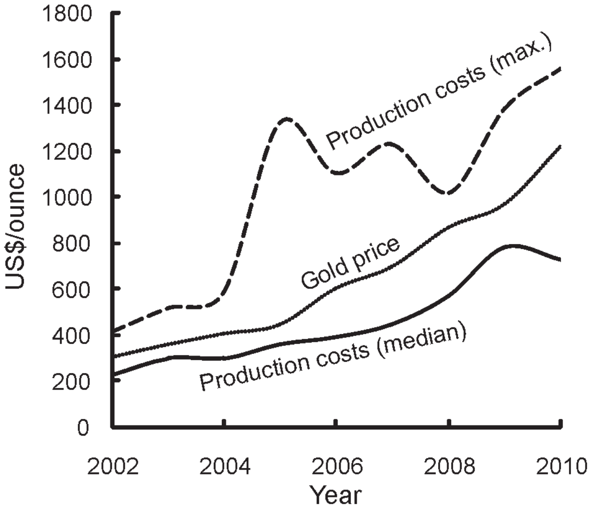

Fig. 19. Change in gold production costs compared to gold price from 2002 to 2010. Median production costs calculated for the 50 percentile of total amount of Au contained in identified resource (data from Raw Materials Data Base, May 2011); also shown are the maximum production costs reported.

mines with the highest production costs up to the year 2005 ceased to exist. Since then, the producers with the highest production costs are without exception deep gold mines at the Witwatersrand, some of which hold considerable Au resources.

Increasing public and political awareness of environmental protection and CO_2-emissions has put pressure on the mining industry. Over the past decade, regular sustainability reporting has become, in addition to the statutory financial reporting, an important improvement in corporate accountability across all sectors of global industry – including the mining industry. The most widespread protocol is the Global Reporting Initiative (GRI 2006) that more recently has been supplemented specifically for the mining sector (GRI 2010). It includes inter alia indicators, such as direct and indirect energy consumption, total water withdrawal, direct and indirect greenhouse gas emissions, emission of ozone-depleting substances and other significant air emissions, total water discharge by quality and destination, total waste by type and disposal method, number and volume of spills, amount of land disturbed or rehabilitated, percentage of land requiring biodiversity management plans, amount of overburden, rock, tailings and sludges and their associated risks, and others. Although still a practice that is waiting to mature, it is expected that with time sustainability reporting will become a prescribed requirement throughout the mining industry. Only then it will be possible to quantify the real costs of mining. It is expected furthermore that mining companies will be asked to carry more and more of the currently external costs. This will put significant pressure on these companies and will negatively influence the conversion of resources to reserves and thus also the future availability of mineral resources.

For some commodities it may be argued that irrespective of the above pressures on the mining industry, market forces will continue to lead to new reserves at a rate comparable to that of consumption in response to increasing prices. This might well be true for metals that are relatively abundant (those with a low Clarke value) in a number of geological environments. For others that occur only in extremely small concentrations, such as Au, the total costs of extraction might become prohibitively high when very low ore grades are reached. For those commodities that are used as source of energy, there must be a thermodynamic limit beyond which mining makes no sense anymore. Once more energy is required to extract a barrel of oil or a ton of uranium from whatever host rock than can be obtained from this oil or uranium, the production of them would be futile unless they can be used for something else that is more valuable (such as plastics from oil).

Mudd & Diesendorf (2010) compiled sustainability data for a number of the largest U-producers and calculated a production-weighted average for water consumption of 692 kl/t U_3O_8, an average energy consumption of 260 GJ/t U_3O_8, and an average emission of 30.8 t CO_2 /t U_3O_8. In the same study these authors also confirmed the exponential increase in energy and water consumption with decreasing ore grade. Almost all U-resources available in the long term are of very low grade, i.e. on the order of 10^3 ppm. For these to be exploited, close to 10 t of rock will have to be mined and milled to produce 1 kg U_3O_8. For comparison, the currently minded U deposits and those that are currently under construction have ore grades that are at least an order of magnitude higher (Fig. 11). Considering the exponential relationship between ore grade and energy requirement, the total energy needed to mine very low-grade deposits, and thus also the associated CO_2 emission, can be extrapolated to be several orders of magnitude higher than now. Following up on the arguments raised by Storm van Leeuwen (2008), Mudd & Diesendorf (2010) calculated a total CO_2 emission from the nuclear fuel chain of 437 g CO_2/kWh for the case of very low-grade ore with 0.01 wt% U_3O_8 as opposed to 117 g CO_2/kWh for mining of ore with 0.15 wt% U_3O_8. Remarkably, the former value is close to the total CO_2 emission from an equivalent combined cycle gas-fired power station, thus challenging the argument that nuclear energy is an effective solution for the fight against global warming (Mudd & Diesendorf 2010). Interestingly, the same ore grade of 0.01 wt% U_3O_8 is also considered the turning point beyond which more energy is being used in the nuclear fuel chain than gained from it (Storm Van Leeuwen 2008). The exact ore grade that represents the thermodynamic limit may be a matter of debate but it is without doubt uncomfortably close to the typical ore grade that characterises our long-term U resources. The trend towards a progressively lower net energy yield or energy return on energy invested (EROI), recently reviewed by MURPHY & HALL (2010), is also seen in other non-renewable energy resources. In the case of crude oil the ratio of energy returned to energy invested dropped from about 100 to less than 10 over the last century. The future exploitation of "unconventional oil" reserves, such as tar sands and so-called oil shales, is likely to depress this ratio into the lower single digits (MURPHY & HALL 2010), thus approaching the thermodynamic limit after which any further exploitation would become useless, irrespective of the price of oil. Unless the future energy demands can be satisfied from predominantly renewable sources, the continuation of the above trend towards lower EROI will invariably have a detrimental influence on future exploitation of mineral resources in general.

7 Conclusions

The few examples presented in this study on the significance of availability forecasts make it possible to draw a number of specific as well as general conclusions. Specifically, our analyses confirmed the contention that global conventional crude oil production is currently at a plateau that most likely represents the all-time peak (Fig. 4). A similar situation was established also for global phosphate production (Fig. 10). The production of P from phosphate rock has reached a plateau in the late 1980s with no evidence of further growth potential for the past two decades. Considering the huge importance of these two commodities for the global energy and food supply, respectively, the recognition of peak production having been already, or currently being reached, has far-reaching consequences for the demands and expectations of a continuously growing world population.

A detailed analysis of the future availability of uranium from primary sources, i.e. ore deposits, revealed that in the medium-term the expected demand can be met. In fact, a considerable overcapacity is prognosticated for the next 10 to 15 years if all projects will be realised as currently planned (Fig. 12). Carrying forward of these overcapacities into the late 2020s and early 2030s will offset a modelled gap between demand and supply but from the mid-2030s a growing shortage of U as fuel for nuclear reactors is forecast if the global nuclear power capacity will be expanded as planned.

For other commodities, such as copper, no meaningful forecasts on the timing of peak production can be made because their production cycle is still immature and is characterised by steady, exponential growth (+3 %/a). In contrast to Cu, which is produced independently in a number of countries, the market for some other commodities, such as the REE, is currently controlled by a single country (China). Such a monopoly carries the risk of short-term shortages on the world market although the global production cycle is immature. No long-term shortage in REE is anticipated because similarly to Cu global REE production keeps following an exponential growth path (Fig. 18) and no meaningful constraints on a peak in REE production can be set.

Our research further highlights that the historically principal gold producer, South Africa, is likely to fade into insignificance as gold producer within one to two decades. All indicators point towards the continuation of the current decline in production, which is expected to lose any global significance by the mid-2020s. This projection is remarkable in so far as the demise of the previously foremost gold province, the Witwatersrand Basin, into irrelevance is not so much for a lack of resources but for prohibitively high production costs because of the depth at which the remaining resources are located. This has major consequences on the global gold production, which is believed to have reached a plateau with little potential for major future growth. Mercury has been shown as an example of a mineral resource whose production cycle is nearly completed, i.e. its global resources are almost completely exhausted and no significant production is taking place anymore.

In general terms, it can be concluded that forecasts on the availability of non-renewable resources are possible, though with highly varying degrees of probability, for some commodities but not for others. Predictions of the times at which we are supposed to run out of certain non-renewable commodities as presented in various media are in many cases based on too simplistic (and sometimes even false) assumptions to an extent that they are effectively meaningless. In terms of both timeframe and reliability, and by analogy with different stages of exploration, three kinds of forecasts can be differentiated: short-term, medium-term and long-term.

Short-term forecasts are best obtained from actual reserve estimates as determined by mining/exploration companies and data on available stocks. By analogy with the error margin on reserve estimates, short-term forecasts should be precise to >80% of the predicted value. As the lead times for mining companies, i.e. the time span for which reserves are defined from identified resources, are typically around five to ten years, this is the timeframe over which short-term forecasts should be applied.

Medium-term forecasts covering time spans of some 10 to 25 years should be based on identified resources, taking cognisance of the fact that even under ideal circumstances at least 10 years would expire from discovery to commencement of mining. Resource estimates are invariably not as precise and reliable as reserve estimates because they are usually a combination of measured, indicated and inferred resources. Consequently, the error margin on these forecasts is correspondingly larger. In practice, the production capacities at the future mines are in fact more important than the total amount of identified resources. Although it is unlikely that production will always take place at 100 % capacity without interruptions or whatever unforeseen problems, projected annual production capacities should provide the most reliable base for medium-term forecasts. Irrespective of the planned capacities, probability of the resource estimates and the geological models used, medium-term forecasts are strongly dependent on other, less predictable aspects, such as political instability in major supplying countries, wars, social unrest, changes in legislation, etc. Nevertheless, they can be useful estimates for formulating general policies.

Long-term forecasts are best obtained from estimates on the total cumulative amount of a commodity that can be extracted (Q_∞) in combination with the extrapolation of historic production cyles. The methods that can be employed in this regard range from Hubbert Linearisation to the parabolic approximation of given production curves by logistic functions (symmetric and asymmetric), Gaussian normal distribution or a number of polynomial functions. Hubbert Linearisation proved to be a very useful method to constrain Q_∞ but only if the P/Q ratio has already become very low, i.e. the production cycle has reached maturity. Comparison of the various sigmoid functions showed that the best results are obtained with a Richards Function, i.e. a general logistic Verhulst Function. They yielded the lowest RMSD and highest coefficients of determination when applied to real data of a mature production cycle, such as the South African gold production. Without a reasonable estimate on Q_∞, long-term forecasts cannot be meaningful – an aspect that has been illustrated with the examples of global Cu and REE production both of which are far from maturity.

With many commodities having become objects of a mature stage of exploration, new technological advances are required (third stage of exploration). Thus the long-term availability is more and more dependent on future exploitation of so-called „unconventional" resources. They are typically of much lower grade and require much more effort, i.e. higher energy input, which moves the importance of sustainability metrics into the spotlight. Taking the true costs of mining, i.e. internal and external costs, into consideration puts into question a number of long-term future projects, such as mining of very low-grade U-ore which would require potentially more energy than can be ultimately gained from the recovered U in nuclear power plants. More precise and reliable data on sustainability parameters for mining operations are called for, but it is most likely that an improvement in the constraints on these parameters will have a negative impact on future ore production. Conversely, the development of entirely new techniques of extracting the desired commodities from rocks might positively influence their future availability. This is, however, effectively impossible to quantify in whatever forecast.

Finally, there is no doubt that the production cycles for a number of mineral and non-renewable fuel resources have reached already a peak or will reach it in the near future. For others, whose production cycle is still immature, it makes no sense to make long-term predictions at this stage. The example of Hg illustrates that technological advances can overcome supply problems. Although the production cycle of Hg, an important commodity in the past, has effectively come to an end, this has had no significant consequences for our societies in general. In fact, considering the toxicity of Hg, the end of Hg production can only be regarded as beneficial to mankind. Its previous use became obsolete thanks to the development of substitutes. The hope remains that similar developments will accompany the decline in other finite commodities, such as the replacement of fossil fuels with renewable energy.

7 References

Al-Fattah, S. M. & Startzman, R. A. (2000): Forecasting world natural gas supply. - Journal of Petroleum Technology, **52**: 62-72.

Ali, S. H. (2006): Gold mining and the golden rule: a challange for producers and consumers in developing countries. - Journal of Cleaner Production, **14**: 455-462.

Bache, J. J. (1987): World Gold Deposits - a Geological Classification. -178 p.; Amsterdam (Elsevier).

BMWI (2010): Rohstoffstrategie der Bundesregierung: Sicherung einer nachhaltigen Rohstoffversorgung Deutschlands mit nicht-energetischen mineralischen Rohstoffen. – 27 p.; Berlin (Bundesministerium für Wirtschaft und Technologie).

Brandt A. R. (2007): Testing Hubbert. - Energy Policy, **35**: 3074-3088.

Canogar, R. (2006): The Hubbert parabola. – Online http://graphoilogy.blogspot.com/2006/09/hubbert-parabola.html.

Cordell, D., Drangert, J.-O. & White, S. (2009): The story of phosphorus: Global food security and food for thought. - Global Environmental Change, **19**: 292-305.

Dumur, D., Pilbeam, C. J. & Craigon, J. (1990): Use of the Weibull Function to calculate cardinal temperatures in Faba bean. - Journal of Experimental Botany, **41**: 1423-1430.

Edwards, J. D. (1997): Crude oil and alternate energy production forecasts for the twenty-first century: The end of the hydrocarbon era. - Bulletin of the American Association of Petroleum Geologists, **81**: 1292-1305.

Frimmel, H. E. (2008): Earth's continental crustal gold endowment. - Earth and Planetary Science Letters, **267**: 45-55.

Frimmel, H. E., Groves, D. I., Kirk, J., Ruiz, J., Chesley, J. & Minter W. E. L. (2005): The formation and preservation of the Witwatersrand goldfields, the largest gold province in the world. – In: J. W. Hedenquist, J. F. H. Thompson, R. J. Goldfarb & J. P. Richards (eds.): Economic Geology One Hundreth Anniversary Volume.- 769-797; Littleton, Colorado (Society of Economic Geologists).

GRI (2006): Sustainability Reporting Guidelines. – 44 p.; Amsterdam (Global Reporting Initiative), www.globalreporting.org.

GRI (2010): Sustainability reporting guidelines and mining and metals sector supplement. – 55 p.; Amsterdam (Global Reporting Initiative), www.globalreporting.org.

Goldfarb, R. J., Groves D. I. & Gardoll, S. (2001): Orogenic gold and geologic time: a global synthesis. - Ore Geology Reviews, **18**: 1-75.

Goulden, J. (2009): Exploration record. - Mining J. Spec. Publ. PDAC February 2009, 1-12.

Hartnady, C. J. H. (2009): South Africa's gold production and reserves. - South African Journal of Science, **105**: 328-329.

Hubbert, M. K. (1956): Nuclear energy and the fossil fuels. - Exploration and Production Research Division Publ. No. **95**, 40 p.; Houston, Texas (Shell Development Company).

Hubbert, M. K. (1982): Techniques of Prediction as Applied to Production of Oil and Gas. - U.S. Department of Commerce. NBS Special Publication, **631**: 16-141.

Jevrejeva, S., Ginsted, A., Moore, J. C. & Holgate, S. (2006): Nonlinear trends and multi-year cycle in sea level records. - J. Geophys. Res., **111**: 2005JC003229.

Leuliette E. W., Nerem, R. S. & Mitchum, G. T. (2004): Results of TOPEX/Poseidon and Jason calibration to construct a continuous record of mean sea level. Marine Geodesy, **27**, 79-94.

McKeith, T. D., Schodde, R. C. & Baltis E. J. (2010): Gold discovery trends. - SEG Newsletter, **81** (April 2010), 1-26, Littleton.

Meadows, D. H., Meadows, D. L., Randers, J. & Behrens, W. W. (1972): The Limits to Growth. – 1st ed., 205 p. (Universe Books).

Mudd, G. M. (2007): Global trends in gold mining: Towards quantifying environmental and resource sustainability? - Resources Policy, **32**: 42-56.

Mudd, G. M. & Diesendorf, M. (2010): Uranium mining, nuclear power and sustainability - rhetoric versus reality. – In: Sustainable Mining Conference, 17-19 Aug. 2010, Kalgoorlie.

Müller J. & Dirner, V. (2010): Using sigmoid functions for modelling South African gold production. - Geoscience Eng., **56**: 44-58.

Müller, J. & Frimmel, H. E. (2010): Numerical analysis of historic gold production cycles and implications for future sub-cycles. - The Open Geology Journal, **4**: 35-40.

Müller, J. & Frimmel, H. E. (2011): Abscissa-transforming second-order polynomial functions to approximate the unknown historic production of non-renewable resources. - Mathematical Geosciences, in press, DOI: 10.1007/s11004-011-9351-8.

Murphy, D. J. & Hall, C. A. (2010): Year in review—EROI or energy return on (energy) invested. - Annals of the New York Academy of Sciences, 1185, 102-118.

Nashawi, I. S., Malallah A. & Al-Bisarah, M. (2010): Forecasting world crude oil production using multicyclic Hubbert model. - Energy Fuels, **24**: 1788-1800.

Norgate, T. E. & Jahanshahi, S. (2010): Low grade ores - Smelt, leach or concentrate? - Minerals Engineering, **23**(2): 65-73.

OECD/IAEA 2010. Uranium 2009: Resources, Production and Demand. – 456 P.; Paris (Nuclear Energy Agency, Organisation for Economic Co-operation and Development).

Oerlemans, J. (2005): Extracting a climate signal from 169 glacier records. – Science, **308**: 675-677.

Richards, F. J. (1959): A flexible growth curve for empirical use. - Journal of Experimental Botany, **10**: 290-300.

Roper, D. L. (1976): Depletion Theory. – 6 p.; http://www.roperld.com/science/minerals/DepletTh.pdf.

RMSG, Raw Materials Supply Group (2010): Defining Critical Raw Materials. - Brussels: European Commission, Enterprise and Industry, 53 p.

Robinson A. B., Robinson, N. E. & Soon, W. (2007): Environmental effects of increased atmospheric carbon dioxide.- Journal of American Physicians and Surgeons, **12**:79-90.

Scherer, R. (2010): Die Bedeutung von Erzlagerstätten mit Gold als Nebenprodukt für die Abschätzung zukünftiger Goldreserven. – Unpubl. Diploma thesis, Institute of Geography and Geology, University of Würzburg.

Simmons, S. F. & Brown K. L. (2006): Gold in magmatic hydrothermal solutions and the rapid formation of a giant ore deposit. – Science, **314**: 288-291.

Soetbeer, A. (1879): Edelmetall-Produktion und

Werthverhältniss zwischen Gold und Silber seit der Entdeckung Amerika's bis zur Gegenwart. – A. Petermann's Mitteilungen aus Justus Perthes' Geographischer Anstalt, Ergänzungsheft Nr. **57**, 141 p., Gotha (J. Perthes); production data at http://www.retrobibliothek.de/retrobib/seite.html?id=104704 (accessed 17.06.2011).

Storm van Leeuwen J. W. & Smith, P. B. (2008): Nuclear Power - The Energy Balance. – Online report: www.stormsmith.nl, Chaam, Netherlands.

Verhulst, P. F. (1838): Notice sur la loi que la population poursuit dans son accroissement. - Correspondance mathématique et physique, **10**: 113-121.

Whitmore, A. (2006): The emperor new clothes: sustainable mining? - Journal of Cleaner Production, **14**: 309-314.

WNA, World Nuclear Association (2010): Supply of Uranium. – 19 p.; http://www.world-nuclear.org/info/inf75.html.

Acknowledgements

Some of the results presented in this study form part of a doctoral thesis by J. Müller at the University of Würzburg. We are grateful to G. Mudd for sharing his sustainability data on U-mining prior to publication and to D.L. Roper for sending his models on global U production (based on a Verhulst fit). The senior author thanks the Akademie für Geowissenschaften und Geotechnologien for the invitation to present this work at its 25th anniversary celebration.