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Comment on: "Recent revisions of phosphate rock reserves and resources: a critique" by Edixhoven et al. (2014) – Phosphate reserves and resources: what conceptions and data do stakeholders need for sustainable action?

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Abstract

Several recent papers predict a scarcity of phosphate reserves in the near future. The paper by Edixhoven et al. (2014), for instance, expresses the doubts about whether the upward estimate of reserves by the IFDC (2010) and the USGS (2010) provide an accurate, reliable, and comparable picture, as they are based on reports that do not clearly differentiate between phosphate ore and phosphate products (i.e., marketable phosphate rock concentrate). Further the indistinct use of the terms reserves and resources is criticized. Edixhoven et al. ask for a differentiated inventory of world phosphate reserves including "guidelines which determine the appropriate drill hole distances." The claim that humanity is on the safe side with respect to future phosphate is supply is doubted as the validity of the IFDC's upgrading of the Moroccan data to 50 Gt phosphate is questioned.

The present paper identifies and discusses basic conceptual errors of the paper by Edixhoven et al. and related papers that predict a short or mid-term phosphorus scarcity. These include the non-acknowledgment of the dynamic nature of reserves (which depends on price, technology, and innovation for exploiting low-grade deposits, etc.), the mixing of finiteness and staticness of the ultimate recoverable resources (i.e., phosphorus that may be mined economically in the long-term future), the improper use of the Hubbert analysis (which, e.g., simply uses the USGS estimates of reserves as a substitute of an estimate of ultimate recoverable resources) and the geostatistical naïve/unprofessional demand for fixed drilling plans to assess reserves.

We reconstruct the IFDC and USGS estimates and conclude that there is no evidence for considering the 50 Gt phosphate concentrate as an unreasonable estimate for Moroccan reserves. However, the partial mixing of different units (e.g., phosphate ore and phosphate concentrate or marketable product) in the USGS data may be avoided by improving the data base and using proper conversion factors. When applying these factors and assess all reserves in marketable Gt of phosphate rock (PR-M), which is a common scale for measuring annual consumption, the magnitude of the

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USGS estimates 2014 of 67 Gt PR reserves does not change essentially yet decrease to 64 (IFDC assessment) to 58.3 Gt PR-M (worst case calculation). We argue that, a better harmonization of the (national) classification systems is meaningful. The discussion suggests that the discrepant estimates of resource estimates that can be found in literature are due to different system understandings, different conceptions of sciences, and diverging worldviews.

Finally, we discuss in what way an independent and scientifically sound assessment of the phosphate resources can be realized in the long-term. We suggest the establishment of a solidly funded, international standing committee that regularly analyzes global geopotential as the source of future resources and reserves. Such a committee may be hosted by international science associations of geoscientists, given that a comparative assessment with other environmental threats reveals that investments in this field are proportional and meaningful.

1 What knowledge do we have about phosphate reserves?

Prospective phosphorus management requires special attention because phosphorus is bio-essential (i.e., unsubstitutable), the phosphorus cycles are of a dissipative nature (with the consequence that the anthropogenic cycle is still causing critical eutrophication in aquatic systems), and phosphate reserves are finite today, tomorrow, and in the distant future. Thus, knowledge about the geopotential of phosphorus, as well as the prevention of non-functioning markets, is an important factor for food security.

But do phosphate reserves become physically scarce in the near future (Cordell et al., 2009; Rosemarin and Jensen, 2013)? Is the update of the Moroccan phosphate reserves by a factor of 10 to 50 Gt phosphate in 2010 (USGS, 2010) a mirage due to geostatistical substandard estimates, or a result of insufficient research based on mixing basic measurement units, or not distinguishing *marketable phosphate rock concentrate* (phosphate concentrate) from phosphate rock? To support distinction, we use the abbreviation PR-M if we deal with *marketable* phosphate concentrate, PR-Ore if we report about phosphate ore and PR when we refer to the data of US Geological Survey Mineral Summaries (USGS MCS). PR-M "varies in grade from less than 25 % to over 37 % P_2O_5" (van Kauwenbergh, 2010, p. 5). In general. 30 % P_2O_5 is taken as a base for conversion to PR-M. Is the classification by the USGS sufficient for sustainable phosphorus management, or do we need a highly disaggregated classification scheme with 10 or more categories? Are judgments that humanity has a "high planning horizon" for phosphate rock reserves (Scholz and Wellmer, 2013) unjustified, as there is no "independent and scientifically sound global inventory of PR deposits" (Edixhoven et al., 2014, p. 504)? These questions are considered in the paper by Edixhoven et al. (2014).

A previous version of the paper (Edixhoven et al., 2013) received severe criticism in three reviews (Cook, 2014; Hilton, 2014; Scholz and Wellmer, 2014). Though some of the criticisms of the extensive reviews have been addressed, the Edixhoven et al. (2014) version still includes many assumptions, statements, and interpretations that, in our opinion, are unacceptable from a raw resources scientist's, a system scientists, and a geostatistical modeling perspective. The paper also takes an insufficient view of the economic mechanisms of the supply-demand system and misses a transdisciplinarity perspective that acknowledges the roles and interests of the key stakeholders.

As may be taken from Hilton (2014), the paper by Edixhoven et al. can be seen as an example of a critical, skeptical contribution on the future availability of mineral commodities. We think that the question of why different scientists or stakeholders provide such different judgments about reserves and resources is of general interest. Thus, this comment discusses in Sect. 7 whether these frequently found discrepancies are due simply to (a) different data, system models, or system boundaries? Are there (b) fundamental reasons that are rooted in different conceptions or schools of sciences? Or can the differences be explained by (c) different worldviews?

Starting in Sect. 2, this paper comprises the research question and main conclusions of Edixhoven et al. Then, we explain why certain fundamental issues are dealt

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with in an unacceptable manner. Section 3 deals with the poor acknowledgement of the dynamic nature of reserves. Section 4 discusses some fundamental problems with respect to mathematical modeling (such as the Hubbert analysis) and geostatistical inference. Section 5 reflects on the granularity of reserves/resources classification and argues that the USGS classification is a proper reference for sustainable phosphorus management. This section also discusses the valuable contribution distinguishing PR-Ore (which is the basis of a reserve) and PR-M, which is a marketable product that may serve as a reference unit from a demand perspective. Section 6 reflects why the assessment of the geopotential is a genuine transdisciplinary issue that requires acknowledging the roles of the different actors and the different epistemics and interests of practitioners.

2 The research question asked by Edixhoven et al. in the paper: are current data on phosphate reserves and resources sufficiently reliable?

The paper by Edixhoven et al. discusses the classification and the data about phosphate rock by the USGS Mineral Commodity Summaries (MCS) (USGS 2010, 2014; see also Kelly et al., 2008) and, in particular, focuses on the increase of phosphate rock reserves from 15 Gt PR in 2010 (USGS, 2010) to 65 Gt PR (USGS, 2010). This increase is due mainly to the increase of the Moroccan reserves from 5.7 to 50 Gt PR, as reported in an IFDC Report (van Kauwenbergh, 2010) and “upward restatements by countries such as Syria, Algeria, and Iraq” (Edixhoven et al., 2014, p. 504). The paper questions whether these data meet “industry best practice” and are “reliable and comparable” (p. 493). Further, the paper criticizes the vague use of the categories reserves and resources, and identifies some data in which phosphate ore and phosphate concentrate are not sufficiently distinguished.

The paper offers the following conclusions: The estimates provided by the IFDC report do not present an “accurate picture” (p. 491). This is “mainly due to a simple restatement of ore resources as ore reserves” (p. 504). The simplified classification

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of using reserves and resources is considered to be insufficient, thus the IFDC report "provides an inflated picture of global reserves" (p. 491).

The paper suggests that the conclusion about the no physical scarcity in the coming decades is not reasoned or is "misleading" (see the title of the discussion paper). The paper finishes with a plea for "mineral resource reporting towards standardized definitions across the minerals, both to serve the needs of globalizing businesses and to allow for mineral availability studies within the context of sustainable development" (p. 503). Here, the use of UNFC (2010) classification, which has 40 theoretical cells (of which 12 respectively 14 are used) is proposed.

3 The dynamic nature of reserves and resources is not properly acknowledged

Edixhoven et al. (2013) acknowledge that "given the economic function of resource classifications, reserves and resources are dynamic" (p. 9, line 14). When studying their paper, however, one wonders to what extent this dynamic concept has actually been incorporated. The authors worry about the depletion of phosphate reserves and quote scenarios (they refer to Rosemarin et al., 2011) in which the reserves are considered static and the reserve / consumption ratio decreases to 48 years (pp. 11–12).

3.1 Learning from the history of the resources dynamics of other commodities

Geoscientists question why the continuous learning processes that can be observed in relation to other commodities around the world are not transferred to phosphate. Why should phosphate miners and explorers be less successful and less creative than their colleagues? A few examples:

- Scholz and Wellmer (2013, Fig. 3) showed that for metals the reserve/consumption (R / C) ratio is far less than that for phosphate. For phosphate, the ratio is increasing, even without considering Morocco. However, let us take the very pessimistic view that the ratio is not increasing but staying

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within a spread of equilibrium values that satisfy the planning scope of mining companies. This is true for all metals with a much lower R / C ratio. For copper, for example, the R / C ratio of about 40 stayed within this spread of equilibrium values despite production that more than quadrupled from about 4 Mio t in 1960 to 17 Mio t today. The question that arises is this: what R / C ratio is satisfactory for a commodity derived mainly from stratabound sedimentary deposits? This question will be answered at the end of this section.

- In the period from 1960 to the present time, the average world copper grade decreased from 2 to 1 % Cu (Schodde, 2010), without an increase in real prices (see Scholz and Wellmer, 2013, Fig. 15).

- With the technological breakthroughs of horizontal drilling and hydraulic fracking, the US has reversed the decline of oil and natural gas production and decreased production costs. Oil production is expected to surpass its 1970 peak in the near future (Fig. 1). The 1970 peak was the peak that Hubbert modeled in 1956 with an error of only one year and the peak that started the discussions about other possible commodity peaks. Hydraulic fracking may also be taken as an example of mining a resource from a new medium (i.e., shale oil production from primary deposits vs. production from reservoir rocks into which the oil migrated); similar innovations may be considered in relation to phosphorus.

- New geologic environments become potential ore deposits due to technological developments. Nickeliferous laterites are one example; in 1950, less than 10 % of world nickel production came from laterites. In 2003, that figure was 43 %, and its relative share is expected to grow (Dalvi et al., 2004); 60 % of the world-based nickel resources are contained in laterite (Kuck, 2013). Now, a totally new type of nickel deposit has been discovered: awaruite, a natural iron-nickel alloy naturally occurring in peridotites, a mafic magmatic rock. Awaruite is easier to concentrate than the sulfidic nickel mineral pentlandite (Kuck, 2013).

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Why should a similar shift not occur in phosphates? In the 1930s, more than 10 % of the world's supply came from guano deposits (USBM, 1935). That share is negligible today and has been replaced by sedimentary and magmatic deposits. Even if no additional sedimentary deposits could be found (which, in our opinion, is highly unlikely), the potential remains for other geologic environments like magmatic deposits, marine phosphorite nodules, and mining of low ore grade. As shown in the case of laterites, it is not justified to conclude the ratio of tomorrow from the ratio of deposit types mined today. Neither is it justified to draw conclusions about today's knowledge of a geological environment to the knowledge of tomorrow, especially after the exploration industry moves in with active exploration activities. The state of knowledge of the geopotential field of the Total Resource Box Fig. 3 (Scholz et al., 2014c) is dynamic, too.

If one examines the phosphate situation, equivalent learning effects can be observed. As an example, the Economic Demonstrated Resources (EDR) of phosphate in Australia shall be considered (Fig. 2). One sees a ninefold increase from 2008 to 2011 in a country with very strict reporting standards. In addition, there are the inferred resources, of which not everything can be transferred into the EDR field, but certainly-judging from geologic experience-the share will be larger than zero. The inferred resources are 2.4 times larger in 2013 than the EDR.

We assume that when Edixhoven et al. (2014) talk about "geocapacity," it is identical to our geopotential field of the Total Resource Box, see Fig. 3 (Scholz and Wellmer, 2013). The authors surmise that not much can be discovered within this geopotential field. However, one wonders why companies spend significant amounts of funds for exploration if this is true, as outlined by Scholz and Wellmer (see also Metals Economics Group, 2012; Scholz and Wellmer, 2014). One also wonders why major mining companies that concentrate on "tier one" projects (large, long-living term projects with prospectively low operating costs and high cash flows) move into the phosphate business if everything has been discovered and is already owned by others (Crowson, 2012).

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Scholz and Wellmer (Scholz and Wellmer, 2013) showed that the R / C ratios for singular, lens-like deposits such as those for copper, lead, or zinc have R / C ratios between 20 and 40. Commodities derived from stratabound sedimentary deposits with a much larger aereal extent than zinc or copper deposits, which can easily be extracted like coal, potash, and bauxite, normally have R / C ratios in the range of 100 or even higher. In order to answer the question of what satisfactory R / C ratios are for a commodity coming mainly from stratabound sedimentary deposits like phosphate, we shall do a thought experiment. We will compare phosphate with two other commodities that are considered by practically every raw-material expert in the world to be not considered critical by commodity experts, iron ore and bauxite, the raw materials for aluminum.

- Gordon et al. (2006) examine the sustainability of various elements, especially copper, and reach this conclusion: "We will see... an increased use of abundant alternative materials, principally iron and its alloys, aluminum and magnesium. We anticipate a gradual transition to reliance on these alternative materials."

- The recent study of the Joint Research Centre of the European Commission on critical metals in the path towards the decarbonisation of the EU energy sector (Moss et al., 2013) does not even consider iron and aluminum worth examining.

- Erdmann and Graedel (2011) compared seven important criticality studies from Europe and the US. None considered iron critical, and only one considered aluminum critical.

Now we are comparing the R / C ratios for phosphate, iron ore, and bauxite, the raw material for aluminum and iron ore, in Fig. 4. Phosphate, iron ore, and bauxite are in the same range. Phosphate, even not taking the Moroccan data into account, is increasing (contrary to iron ore and bauxite, which are decreasing) mainly due to the rapid increase of Chinese consumption since 2000, which cannot be followed immediately by exploration successes to keep the R / C-ratio constant.

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We may conclude the following: taking the dynamics of reserve and resource development into account and comparing phosphate with two commodities, not considered critical by commodity expert, iron ore and bauxite, there is no reason to worry about phosphate depletion even in the mid-term future.

3.2 The confusion between finiteness and staticness of reserves

The dynamics of reserves are also important for properly understanding scarcity. We speak about (global) scarcity of phosphate (PR) if the (world) demand for PR needed for food production or other essential societal activities cannot be fulfilled at feasible costs. In this definition, we exclude undersupply due to nonfunctioning markets as a result, for instance, of war, low GDP economics, geopolitical factors, etc. (Brooks, 1965; Zwartedyk, 1976). Scarcity is thus a factor that results from the geoscientific accessibility of phosphorus, the knowledge about its distribution, the availability of technologies for recovering or extracting phosphorus, and the lack of opportunities to adapt or reduce phosphorus consumption or demand. An important and often-neglected aspect of the dynamics of mineral resources is the rule of the "feedback control system" by which reserves increase with price (Wellmer and Becker-Platen, 2002). What does this mean for phosphorus?

Scholz and Wellmer (2013) calculated that in 2011, each world citizen consumed on average 30 kg PR-M. Given a price of 200 USD t^{-1} PR-M in 2012 (which came down to a magnitude of 100 USD t^{-1} PR-M in 2014, Index Mundi, 2014), the average annual cost would be about USD 6 per person. Ceteris paribus, i.e., assuming that nothing else changes, we may ask whether a price of 60 USD per person would bankrupt the world economic system. We may think about the annual costs of energy as a reference for comparison. In 2012, the world population consumed about 10 bio tons of oil equivalents (toe), i.e., 1.43 toe per person (Wellmer, 2014). For an order of magnitude calculation, roughly 60 % of the consumption is oil/gas, which costs about 750 USD per ton (1 barrel costs slightly over 100 USD). Given a conversion factor of 1.5 from 1 t coal to 1 toe and a price of 75 USD for 1 t black coal (Index Mundi, 2014), the average

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energy cost per world citizen in 2011 amounts to a magnitude of about 700 USD, which is about 100 times the current cost of consumed PR-M per person. We may conclude that humanity would not collapse if the costs of PR-M per world citizen were to increase by a factor of 10 to 60 USD (or even higher) per year (although such a price increase might worsen social inequity of having access to phosphorus). From a global perspective, PR-M is a low-price commodity and thus may have a "flexible price" (Scholz and Wellmer, 2013).

Scholz and Wellmer (2013) provided an estimate of the URR (ultimate recoverable resource) of the Western Phosphate Field (WPF) in the US, one of the largest phosphate provinces of the world, of an amount at least 1000 times 178.5 Mt PR-M (2010 world production) supply, to indicate that there will be no necessary physical scarcity in the near future. This, of course, is a first (rough) expert judgment rather than a sourced calculation. Edixhoven et al. (2013, 2014) are querying this estimate. Without repeating the arguments of Scholz and Wellmer (Scholz and Wellmer, 2013, 2014), certain principle aspects shall be pointed out when looking far into the future of the technology of exploitation:

- Mining in the future will be by remote control, as already utilized in the Kiruna iron ore mine in Sweden. Thus, the geothermal gradient is of less importance. Scientists in the 1970s and 1980s trying to judge if a mineralization could be classified as a resource were hardly able to foresee this advance in technology.

- The increasing losses related to going deeper in underground mining using the conventional room and pillar mine system can be avoided by using longwall mining methods with hydraulic roof support, which are already used in Germany in coal mines to a depth of 1500 m.

- The EU is considering supporting research for discovering and exploiting mineral resources down to 3000 m, which is seen as the mine of the future.

- The above estimate for future WPF reserves is an estimate for reserves in 300 years. Given the flexibility of the price and fundamental innovations in min-

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ing technology, the WPF is only of interest if more easily accessible reserves are consumed first.

Naturally, the *dynamics of the demand* must also be incorporated, and it is clear that the factual consumption of PR equivalents (please note also that nonprocessed phosphate rock is used in agriculture) is globally increasing in the next years. Currently, this is due mostly to inefficient use, primarily in Asian countries (Sattari et al., 2012; Scholz et al., 2014). There are many indicators of the inefficient (over)use of phosphate fertilizer today. An input to the agro-food chain at the magnitude of 200 Mt PR-M annually may suffice to feed an increasing population if food production becomes more nutrient efficient.

An estimate of the URR of the WPF was made in order to demonstrate how resources may become reserves. A fundamental error made by Edixhoven et al. and several others is that they mix finiteness and staticness. The world's phosphate ores are finite, but they are not fixed. The phosphorous content of the Earth, meaning the mass of the Earth multiplied by the background value, or the clarke, is an upper threshold. The URR related to PR-M depends on technology, geopotential, and the economic power of humankind. Physical scarcity becomes real if humanity does not have the economic (i.e., financial capital) and other means (i.e., alternative agricultural technologies or innovations for mining low-grade ore) required to produce the amount of PR-M needed to sustain the world's food supply. Reserves and the URR are dynamic variables, and we are far from providing a good estimate on the URR of phosphorus at the global level.

4 The interaction between reserves/resources and supply markets

Any mathematical or geostatistical model is conditional on certain prerequisites. If these prerequisites do not match fully (in mathematics) or to some extent (in application), the use is meaningless. The first section discusses severe misapplications of the

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Hubbert Curve. The statement “peak phosphorus hypothesis is hotly debated” (Edixhoven et al., 2013, pp. 4, line 29) correctly describes the discussion among resource scientists. However, from an applied mathematics perspectives, there is no doubt that the Hubbert analysis cannot be used for estimating the global URR as the basic prerequisites are not fulfilled (Brandt, 2010; Rustad, 2012; Vaccari and Strigul, 2011). The second section refers to the naïve geostatistical wish to “obtain guidelines which determine the appropriate drill hole distance for the various resource classes for the Moroccan deposits” (p. 22).

4.1 The Hubbert Curve works only for supply-driven markets under some constraints

There has already been much criticism about the grossly inaccurate application of the Hubbert analysis for estimating the ultimate recoverable PR-M. The interested reader may refer to the papers of Mew (2011), Rustad (2012), Scholz and Wellmer (2013), Vaccari and Strigul (2011), or to the Appendix.

Nevertheless, it is most amazing that the fallacious application by Cordell et al. (2009) is still highly cited and received status as a “hotly debated” issue for the case of global phosphate reserves. The Appendix analyzes in some detail under what conditions Hubbert was able to provide a remarkable prediction for the ultimate US oil reserves, why the situation for global phosphate reserves differs completely, and why – due to the new technology of fracking – Hubbert’s prediction was also wrong for the US (see Fig. 1).

In this place we summarize the basics of the misapplication in a way that becomes understandable for those who are not used to working with mathematical models. After approximately a century of extensive exploration of and recovery from US fields, Hubbert had a realistic estimate of the future ultimate recoverable resources (URR; Harris, 1977, see Appendix). Further, Hubbert was facing a supply-driven market, meaning that all oil produced was immediately bought on the market. Based on this, he postulated that the curve of the annual consumption of oil could be described by a (symmet-

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ric) logistic curve. Hubbert earned fame by predicting the peak oil of US oil production with only a one-year deviation.

The situation for global phosphate is completely different as opposed to the US oil production. We are far from assessing the magnitude of the ultimate recoverable resources (URR) (which includes the PR-M that will be mined by humanity in the long-term future, plus what has been mined in the past). Given that phosphate concentrate is a low-cost commodity and the potential for technological progress (e.g., if prices rise), the 300 Gt PR resources (USGS, 2014) of today are with the utmost likelihood an underestimation of URR (see Appendix). The major inconsistency of the "peak phosphorus in the near future" statement is that Cordell et al. (2009) used the USGS data of 15 Gt PR of the 2008 reserves for an estimate of the URR. This certainly provides an underestimation of much more than factor 10. Further, the global phosphate rock market is, by no means, a supply-driven market. In addition, the modern Hubbert analysis, which is based on a curve fitting of the production curve by a logistic function, does not provide meaningful results; it just predicts the total URR of 16 Gt PR, about half of which was mined in the past.

The Hubbert Curve may work if there is a supply-driven market with a well-confined ore body, such as the Nauru Guano deposit on Nauru island (Déry and Anderson, 2007). However, applying it to a global estimate of future PR reserves with today's knowledge does not be substantiated by scientific arguments.

4.2 Drilling plans have to be adjusted to sites and interests

Edixhoven et al. criticize "the underreporting of Moroocan resources" (p. 502). The authors are "looking for guidelines which determine the appropriate drill hole distance" (p. 503) and refer to a "geological yardstick adopted in industry for measured reserves" (p. 503). Unfortunately, the authors leave unspecified who needs what information, with what level of certainty, at what costs. If we translate this issue into geostatistical decision theory, the complexity of the issue becomes evident. The question reads: given a decision-maker's interest (related to research, business, public interest, etc.)

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in global/regional/local phosphate reserves and certain prior knowledge as well as financial resources, how many drill holes of what density (e.g., assessed by minimum or mean distance) according to what metric (Euclidian vs. non-Euclidian) and what statistical design or plan (square, triangle, Bayesian, etc.) of what type (diameter, depth, etc.) should be made for analyzing what parameters (volume, mass, purity, profitability, etc.) at what spatial system (system boundaries), if there is certain prior knowledge and financial resources, will best fulfill the decision-makers' interests (Chilés and Delfiner, 2012; Diggle and Ribeiro, 2007; Matheron, 1963; Nothbaum et al., 1994; Wellmer, 1998)?

From a company's perspective, completely different drilling plans are needed for the exploration of the magnitude of the potential excavation volume of a mining area, the elaboration of a business plan (including, for instance, information used in the application of credits), and for optimizing operations when the production is ongoing. There is no panacea, no bureaucratic guideline or policy order for a standard drilling plan. This also holds true for the Moroccan occurrences, with four plateaus with a total size greater than 10 000 km^2 (van Kauwenbergh, 2006, p. 284). The plateaus show a "very complex tectonic history" (p. 273), where you find both highly heterogeneous and homogeneous ore bodies. A drilling plan depends on geologic models and the site-specific exploration history that, in this case, goes back to 1908. If we were to follow the ideas presented by Edixhoven et al. (p. 503), we would apply a square drilling plan with a (minimum) 1 km drilling distance. This would result mechanistically in 10 000 drillings and would not only ignore geostatistical state of the art knowledge but also be, most probably, of limited interest to the OCP (Office Chérefien de Phosphates) and others. How important the local knowledge of experienced geologists (a "competent person", according to the standard JORC code for reserve classification, JORC, 2012) is can be gathered from a comparison with coal, a commodity derived from comparable strataform deposits. In the newest guidelines for the coal reserve classification in Australia, a recommended drilling grid has been deleted, and responsibility rests totally on the "competent" person to decide whether the continuity between points of observation

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is such that, e.g., it qualifies as an indicated resource under the JORC Code, the lowest category to be included in the USGS reserve category (Australasian Institute of Mining and Metallurgy, 2014).

5 The granularity/granulation of classifying the global reserves/resources must be functional

5.1 The constraints of granularity have to be considered

We fully agree with the demand made by Edixhoven et al. (2014) that the global estimate of phosphate reserves and resources must be reliable and comparable. One has to take into account, however, certain basic parameters and constraints:

- reserve and, even more so, resource calculations are *estimates*. Although the JORC code (2004) and all other equivalent codes require a competent person with at least 5 years experience in the relevant ore-deposit type, there will always be discrepancies between the estimates of two different "competent persons." *Reserve/resource classification is not an exact science.*

- *Reserve data are normally determined by private companies*. For them, reserves comprise their working inventory. The reserves may be more dependent on business planning models and investment alternatives than on the magnitude of minerals in the ground. Companies normally have no interest in spending funds on determining reserves far into the future. As long as we operate in a free market system, this will always be the case, and the further we look into the future, the less exact the company data will be.

- Consequently, if we look at JORC reserves and resources and envision a future mining sequence, there is a correlation between the data of potential future mining and the accuracy of tonnage and grade figures. This has a further consequence: the *granularity* depends on the knowledge and, thus, *is time dependent*.

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The JORC reserves and resources will be mined first. For them, a high degree of granularity exists. For the potential reserves and resources that do not yet fulfill JORC criteria and can only be transferred into the higher categories after further exploration, far less detailed granularity is justified. There are no worldwide data available, except for Australia, that can provide a rough idea about the relationships. The Accessible EDR (Economic Demonstrated Resources) that the USGS takes as reserves for Australia in the Mineral Commodity Summaries (Christesen, 2014) contains 33 % JORC reserves in 2013 (Geoscience Australia, 2014).

- The JORC Code and other national and international (finance-related) codes orient themselves as *investors' needs to know*. They provide information for a quantitative risk assessment for a mining company's investment. The United Nations Framework Classification (UNFC) had to follow this granularity; otherwise, it could not achieve the aim of making different classification schemes comparable. (Because it is constructed as a three-dimensional matrix with a numerical codification, not all theoretically possible combinations are relevant in the real world.)

- *Granularity can be compared to a measuring tool*. It has to be appropriate for the quality of the data. One is not measuring the thickness of a broomstick with a caliper at an accuracy of 0.01 mm. Do we really have detailed-enough economic criteria for reserves or resources that will be mined 100 years and more from now? Who would have dared in 1900, when the average copper grade in the US was around 2.5 %, to forecast that 70 years later, the lowest average grade of a copper mine in Canada would be 0.4 % Cu? Today, the lowest-grade copper mine is the Aitik mine in Sweden with 0.27 % Cu (Scholz and Wellmer, 2013).

- In our opinion, the perfect granularity for assessing future availability was the *reserve base* category of the USGS MCS. The reserve base was independent of short-term variations in price or other short-term economic factors, and was changed only by losses from production and increases from discovery and technological improvements (USGS and USBM, 1982). In Fig. 4 of Scholz and

Wellmer (2013), three examples are shown comparing reserves and reserve base of the USGS. The reserve base / consumption ratio of the metal examples, copper, nickel, and cobalt, is about twice the R / C ratio. Figure 4 of this paper shows the R / C ratios for phosphate, iron, and bauxite based on reserves and reserve base. It can be concluded that the reserve base of these commodities is one-and-a-half to nearly three times higher than the reserves.

For estimating the reserve base of a commodity, cost models are necessary. These were supplied by the US Bureau of Mines, which no longer exists. Because the cost models could not be updated any longer, the USGS discontinued to quantify the reserve base category in 2010. Taking into account that all governmental earth science organizations in the world are under considerable financial pressure, it is not likely that the basis for a new reserve base estimate can be created in the near future.

Thus, the question arises of what granularity is appropriate for reserves and resources of phosphate that can be mined in 100 years and more from now. One must also take into account that an assessment of resource data of one nation can be more detailed than the average assessment of the whole world. Despite the efforts of the UNFC, the data for one country will always be more homogeneous than a worldwide data set. Australia is a good example of how much aggregation is necessary and how much detail is possible in a final report. Australia had a sophisticated reporting system in place for years. As Fig. 5 shows, for the most-important Economic Demonstrated Resources (EDR), 20 subcategories of the UNFC system are lumped together. Concerning the JORC classification, four categories are combined in the EDR: proven and probable reserves and measured and indicated resources (Geoscience Australia, 2014, Fig. A2, p. 172).

Taking the above framework conditions into account, it seems reasonable that the USGS distinguishes only two quantitative categories in its reports in the publication MCS: reserves and resources.

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As outlined above, the requirement of a competent person under the JORC code applies correspondingly to global reporting systems like that of the USGS. There can be no doubt that the USGS mineral commodity specialists responsible for their chapters in MCS and in the Minerals Yearbook as well as the IFDC experts have seen many phosphate deposits worldwide and are very experienced long-term ore deposit experts who can draw many comparisons between deposits under exploitation and those still not exploited, and can judge as best as possible which publicly available information should be taken into account for the category "reserves" and which falls into the category of resources.

5.2 International harmonization of the classification is meaningful

Nevertheless, conformity among the different national classifications seems reasonable. The case of the Iraq reserves may be taken as an example, where "USGS restated from zero to 5800 Mt PR overnight in 2012" (Edixhoven et al., 2013, p. 1021) and "downgraded again by 93 % to a mere 430 Mt PR . . . " (p. 500). Please note that the Iraq data in the USGS MSC are factually based on PR-Ore data (see below). The uptake and correction of the Iraq data was neither a clandestine directive nor did 5370 Mt PR-Ore disappear. As has been well reported (Al-Bassam et al., 2012), the exploration of the 22 Iraq occurrences including 7 deposits and a resource estimate of 9.5 Gt PR-Ore has been underway since 1965 by the Iraq Geological Survey and its predecessor organization. Exploration and drilling began in 1963. For all deposits, "pilot scale beneficiation" was done "using simple beneficiation techniques" to check whether PR-M could be produced with the available technology (Al-Bassam et al., 2012). The story of the USGS data is that the exploration in Iraq obviously reached a certain level of maturity in 2011. Unfortunately, for historical reasons the classification system labeling the Iraq reserves was the Russian system (Gert, 2007). In addition, this system distinguishes between "reasonably assured, identified, estimated, and inferred" recoverable reserves. A second look revealed that, only some fields fulfilled the USGS criteria for reserves. The downgraded reserves did not disappear, but some reserves were down-

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graded to resources (Jasinski, 2013) and may appear as resources in the future after further exploration or increases in prices.

5.3 Mixing PR-Ore and PR-M (marketable phosphate rock concentrate) may be avoided

A main achievement of the Edixhoven et al. paper is the revealing of the mixing of PR-Ore and PR-M data in the USGS MSC. USGS attempts "to use reserves in terms of concentrate, but many of the foreign sources are reported in terms of ore and grade. The country specialists provide official information, if available, and some of it is reported in terms of ore and grade... Data for Algeria, Syria, Iraq, South Africa are in terms or ore. US data is concentrate" (Jasinski, 2014b). The USGS MSC 2014 (p. 119) explicitly mentions this but did not specify for which countries ore data and for which countries concentrate data are used. The question that must be answered is whether this situation essentially changes the current estimate of global phosphate reserves.

For phosphate rock reserves the entry into the USGS MCS for 2014 is 67 Gt. We know from Jasinski (2014b) that the US entry is marketable product (PR-M). According to van Kauwenbergh (van Kauwenbergh, 2006, 2010), also the Morocco and Western Sahara entry is PR-M. For Australia we know that the entry into the MCS is Accessible Economic Demonstrated Resources (EDR). Geoscience Australia (2014) reports that the Accessible EDR contains 213 Mt of P_2O_5. Taking the average of 30 % P_2O_5 for PR-M this results in 0.71 Gt PR-M instead of 0.87 Gt in the USGS MCS.

As said above, the USGS conveyed (Jasinski, 2014a). the entry into the USGS MCS for Algeria, Syria, Iraq and South Africa is in terms of PR-Ore. Because we do not have information for the other remaining countries in the MCS we assume the worst case and assume that the entries also present PR-Ore. So we group all countries besides the USA, Morocco and Australia together. We will examine an investigation by van Kauwenbergh (2010) who investigated the 2010 entries of the USGS MSC to derive a number for PR-M (IFDC Reserves Product; van Kauwenbergh, 2010, p. 33) and do

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in addition a *worst case calculation* for all countries except US, Morocco and Western Sahara and Australia for which we have data in the MSC.

If we do not take Morocco and Western Sahara, USA, and Australia into account, according to the investigation of van Kauwenbergh (2010), the conversion rate from USGS MSC 2010 entries to PR-M would be 0.8, i.e., meaning a reduction by 20 %. For our *worst case calculation we a*ssume an average grade of 20 % P_2O_5. Magmatic ores are mostly lower, but most sedimentary ores are of higher grade. Also the benefication efficiency is higher for magmatic phosphates producing phosphate concentrate with more than 30 %. 20 % P_2O_5 ore grade means that we theoretically need 1.5 t of PR-Ore to produce 1 t PR-M with 30 % P_2O_5. Now we have to consider the mining and benefication efficiency. Scholz et al. (2014b, pp. 48–53) intensely discuss two estimates of recent mining efficiencies, one of the IFA (International Fertilizer Industry Association; Prud'homme, 2010) and one from the IFDC (VFRC, 2012). We take the average of both which is 66 %. This means instead of needing theoretically 1.5 t of PR-Ore to produce 1 to of PR-M we need in reality 1.5/0.65 = 2.3 t of PR-Ore for 1 t PR-M.

If we transfer this to the entry of the MCS, we have the entry total reserves minus the reserves for the US, Morocco and Western Sahara, and Australia, i.e., 67 – 52 = 15 Gt, of which we do not know if it is PR-Ore or PR-M. Taking the investigation of van Kauwenbergh of 2010 as an analogon, 15 Gt PR-ore would convert into 12 Gt PR-M. Taking the worst case scenario of above 15 Gt would convert to 6.5 Gt. In consequence the total MSC-entry for PR-M would change in the case of the van Kauwenbergh, 2010, analogon to 64 Gt (and with a correction for the Australian entry to 63.8) and with the worst-case scenario to 58.5 Gt (and with a correction for the Australian entry to 58.3 Gt). This correction induces that the global share of Moroccan reserves becomes significantly higher as the non-Moroccan reserves get halved under a worst case assumptions.

It is interesting to consider the relative error. In the case of the van Kauwenbergh analogon the error relative to the MSC entry would be 5 %, in the worst case scenario 13 %. Although it is not directly comparable it might be helpful to compare it with errors

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tolerable in standard reserve calculations. If we take again a comparison with coal, being geologically similar, for example: for the accuracy of coal reserve estimation for a detailed feasibility study ±10 to 15 % is acceptable (Standard South Africa, 2004).

5.4 The Moroccan reserves are underestimated rather than overestimated

We will now discuss the IFDC's estimate of the Moroccan reserves. According to van Kauwenbergh, "The phosphate rock resources of Morocco are extremely large and apparently still incompletely explored" (van Kauwenbergh, 2010, p. 35). In 1989, for instance, the OCP reported that 36 % of the Khouribga, 18 % of the Ganntour deposit, and 56 Gt mineable reserves were explored (Savage, 1987) with a first estimate of 140 Gt. These data obviously refer to PR-M (van Kauwenbergh, 2013). In 1995, the aggregate resources had increased to 85.5 billion cubic meters, which equates to somewhat between 171 and 214 Gt PR-Ore. If we assume that the density of phosphate ore rock is between 2.0 and 2.5. Also the Gharbi data from 1998 are in cubic meters; given an exploration of 45 %, "the identified reserves of the Khouribga region were 37.37 billion m^3" (Gharbi, 1998, p. 128). This estimate was obviously due to the easy accessibility of the upper beds. IFDC suggested a conservative conversion factor of 2 and updated the Khouribga data in 2011 based on the production data at this mine, suggesting a reserve of 28 Gt PR-M (van Kauwenbergh, 2010). Similar differentiated and obviously conservative estimates were given for two other areas, i.e., the Ganntour and Bu Craa deposits. This provided a reserve estimate of 51 Gt for three mining areas no including the Meskala, But IFDC assesses the four phosphate rock regions to include approximately 170 Gt PR-M. Assuming that "regions that have not been explored contain phosphate rock that is similar in thickness and in other properties to the existing reserves are considered, the combined identified resources and hypothetical resources of the four areas are estimated at approximately 340 000 mmt" (i.e., 340 Gt; van Kauwenbergh, 2010, p. 36).

The IFDC report stresses that the production costs are not assessed but will increase by various factors, such as the increase of the carbonate content in some ores. Given

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the present exploration, the ore grades of the explored fields are exceptionally high and, on average, well above 30 %. With respect to cost development OCP conveyed that the company had (roughly) estimated the cost for producing PR-M for reserves far above the 50 Gt PR-M which are recorded in the USGS-MSC (Terrab, 2012).

Moroccan mining activities are in a permanent development. For several years, three new mines at Khouribga and one at Ganntour have been under development (OCP, 2014). Given an almost 100 year history of exploration and the specifics of the geological setting, it is clear that different parts of the 10 000 km^2 are on different levels of the exploration ladder (Marjoribanks, 2010). Furthermore, in many places the distinction whether reserves or resources are "demonstrated (measured and/or indicated) and identified (demonstrated and/or inferred)" (Edixhoven et al., 2014, p. 497) develops over time as a combination of multiple evidences from continuing exploration and mining experience. Against this background, the conclusion that "the increase of Moroccan reserves . . . was . . . due to simple restatements of ore resources as ore reserves" (p. 497) seems to be a very biased statement which is far from properly acknowledging the available data and the documented history of continuous exploration and mining activities.

6 Improving the dialogue between those with knowledge in science and those with experiences from practice

The assessment and management of the geopotential of the resources and reserves of phosphorus is a complex, societally relevant issue that has to be addressed by relating knowledge from the various stakeholders and a wider range of scientific disciplines. To simplify, we are facing two processes. One is a multi-stakeholder discourse in which different economic key agents (mining companies, traders, investors/banks, national agencies, environmentalists, etc.) generate, communicate, and benefit from geologic, market, or other data that are relevant to their interests. On the other hand, the multi-stakeholder knowledge from practice is complemented by scientific knowledge, the

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primary motivation and goal of which should be to provide a valid description of reality. In the last two decades, transdisciplinarity has become a method for utilizing and applying science to the processes of mutual learning between science and practice (Scholz et al., 2000; Thompson Klein et al., 2001).

Transdisciplinarity acknowledges the different modes of knowledge that are owned by practitioners (e.g., experiential wisdom about geologic or market properties that has become an entry in many regulations related to mining) and science (e.g., technology development or theories about the genesis of sedimentary phosphate layers). Transdisciplinarity accepts the different roles of different key stakeholders and provides benefits by relating different epistemics (i.e., ways of knowing) on the prevalence and dynamics of phosphorus reserves. One important prerequisite is the understanding of the constraints, the accepting of the otherness of the other and to cope sensitively with the constraints of key actors such as mining companies. To better understand the dynamics and pitfalls of phosphorus management, a "collaborative effort by phosphate rock producers, government agencies, international organizations and academia will be required to make a more definitive current estimate of world phosphate rock reserves and resources" (van Kauwenbergh, 2010, p. 1).

Julian Hilton, in his extensive critique of the first version of the Edixhoven et al. (2013), has done an excellent job of describing many facets that characterize the rationales of key stakeholders. Let us look at just a few issues that demonstrate the complexity of phosphorus management: "Major mining companies are notorious for understating reserves, while juniors tend to overstate because they want to attract investors"; "Many emerging/developing countries depend heavily on their P resources . . . so resource data may be withheld for commercial and/or strategic reasons . . . "; "Large resource-hungry countries such as China will guard PR resources as strategic resources and hence not disclose quantities available . . . "; "The Era-MIN network . . . estimates an increase of some 50 % in resource quantification" by "improved exploration and analytical techniques." Or the issue that in developed countries is a "social license to operate." Phosphorus mining is a matter of political decision-making that may

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be reversed. Based on these factors, it becomes less and less likely that the major PR producers will disclose their hands, especially where the production base is financed through the world's stock exchanges . . . " (all quoted from Hilton, 2014, pp. 2–3).

Against this background, the paper by Edixhoven et al. looks like a strange academic desktop study that is missing the interaction with practitioners to understand (i) the knowledge gained in exploration and mining operations/companies and (ii) the constraints faced by different stakeholders when dealing with reserve data. Applying a "tone of moral indignation with . . . the intention to shame PR producers into disclosure of the reserves and resources they hold" (Hilton, 2014) is certainly not an acceptable strategy. Transdisciplinary processes, such as those induced by the Global TraPs project on "Sustainable Phosphorus Management" (Scholz et al., 2014a), in which representatives from all key stakeholder groups participated, are a necessary means of learning both for practice (e.g., to better understand the complexity and long-term issues of sustainable resources management) as well as from scientists to acknowledge the multiple contexts and constraints to which a reliable access to reserve data is exposed.

7 General discussion and conclusions

7.1 There is sufficient knowledge for estimating phosphate reserves and resources

PR-Ore and PR-M have to be distinguished: The main contribution of Edixhoven et al. has been that data on phosphate rock ore and phosphate concentrate (both abbreviated as PR in their paper) are sometimes not properly distinguished. Given that the ore is economically mineable, the conversion factor depends, among others, on ore grade and the efficiency (or losses) of recovery and losses in the process of beneficiation. The overall USGS MCS include data for four countries which provided or data for which no conversion from PR-Ore to PR-M has been performed. And there have

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been 16 countries where no specification on the national reporting was provided by USGS. A rough worst case calculation indicated that-if we take *marketable* phosphate rock concentrate with 30 % P2O5 (PR-M) as the measuring unit-the current global reserve estimate amounts to 58 Gt PR-M (which is about 13 % smaller than the USGS estimate).

Initiating a process of consenting on a proper granularity of reserve estimates: Mine-specific, national, and global classification systems have different functions and ask for different levels of accuracy. From a global perspective, both with respect to providing reliable information for functioning markets as well as for assuring long-term supply security, a simple, feasible, and sufficiently reliable classification system that is acceptable to all key players is helpful. We argue that the distinction between reserves, reserve base, and resources (USGS and USBM, 1980) has been such a system. Since the reserve base category cannot be quantified anymore, there are now only the two categories, reserve and resources. We argue that the detail of the data of these categories are sufficient to analyze the dynamic natures of reserves and resources.

There is no physical scarcity of rock phosphate in the near future: We could not identify evidence that there will be (a necessary) physical scarcity of phosphorus in the next decades or centuries. The Hubbert Curve analyses on global reserves, which suggest scarcity, are unacceptable applications of the Hubbert approach. They either underestimate future reserves by more than a magnitude of factor 10 (in the case of curve fitting without a URR, i.e., modern Hubbert analysis), or they work with misunderstood estimates of URR (i.e., when taking the USGS data on reserves as an estimate of URR). Phosphate rock is a low-cost commodity, and prices are very flexible; in addition, phosphorus reserves have the potential to increase easily due to technological advancements like economic underground mining.

The Moroccan reserves are big: Based on almost 100 years of exploration and mining, it is clear that Morocco (including the Western Sahara area) owns the largest currently known phosphate resources in the (terrestrial) world. Given an annual production rate of 0.028 Gt PR-M in Morocco and a current annual demand of 0.2 Gt PR-M, there

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are no incentives or needs for the national company to assess exactly what parts of the approximately 200 Gt PR-Ore (if we, for example, refer to the 1995 estimate of 171–214 Gt PR) identified may be mined economically with today's costs. However, according to the data publically available or provided by the OCP, there is reliable evidence that at least 50 Gt PR-M may be mined with the current mining regime. It is important (and has not been properly acknowledged) that the exploration of the Moroccan reserves is an ongoing process and increasing multiple evidences (not only the last century's drilling data) substantiate such an estimate.

Developing a proper understanding of the accuracy of reserve estimates: The assessment of the current economically mineable phosphate ores is not a matter of exact science. Given a magnitude of 0.2 Gt PR-M phosphate concentrate of annual production and a magnitude of 60 Gt PR-M as global reserves, no one would be willing to pay for reliable information about what might be produced in 300 years for today's costs. Also against this background, it is unfortunate that the basis to quantify the reserve base does not exist anymore (see above). When providing an assessment on the current phosphorus reserves, it is important to acknowledge that the reserve estimates are provided sometimes by companies that historically worked with different classification systems such as the Russian, Australian, Chinese or others or that of the USGS. Thus, the 22-country data of the USGS MCS 2014 do not all have the same basis. It is also evident that a highly differentiated and costly assessment applying the JORC or equivalent classification systems (which are prescribed by the major stock exchanges) is not meaningful for an estimate of global reserves. An overly "detailed granularity" for a global assessment seems to be dysfunctional and naïve. Nevertheless, requiring transparency and compatibility of data is a meaningful suggestion, though we have to ask how this may be achieved (see below).

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7.2 Why do we have so different estimates of reserves and resources?

7.2.1 Are there differences in estimates due to misinterpreting data or systems?

In principle, both camps, the optimists and the pessimists, use the same data but interpret them differently.

- The physical scarcity and postulated peak phosphorus in 50 to 100 years hypothesis may be taken as an example. Some scientists, who generally do not come from the fields of geosciences or applied mathematics, consider the issue hotly debated. We showed that such a position completely results from a fundamental misuse of data and of the systemic prerequisites of doing a Hubbert analysis. No one who takes a closer look at the calculation would accept that the USGS data on (today's) reserves (i.e., on those parts of the global phosphorus ores that are known and may produce phosphate concentrate at today's costs and with current technology) might be taken as an estimate for what may be ultimately recovered in the long run. Likewise, the prerequisite of a modern Hubbert analysis of the global phosphate URR, based on a logistic curve fitting of the cumulative production, does not function. It provides a future reserves estimate that is by a factor of 10 smaller than the currently known reserves.

- Reserves in the USGS MCS comprise the categories proven and probable reserves and measured and indicated resources (according to the JORC standard). The four large-scale fields in Morocco have been the subjects of exploration as well as mining for almost 100 years. There is a magnitude of 200 Gt PR ore identified by the OCP. The average ore concentrate is above 30 %. More than 45 % of the largest field of Khouribga is explored by measurements. What are the geostatistic or scientific reasons for discussing yardsticks with 25 boreholes "per square kilometer," given a total area of 10 000 km as mentioned by Edixhoven et al.? Who should pay for the drillings, and what value does this information have? The data from Morocco have been analyzed and evaluated by IFDC in

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a multi-year project. The data, conversion factors, etc. have been discussed with World Bank and other experts. Based on this, an inferred estimate of 50 Gt PR-M may be judged as conservative.

- The comments on the jumps in the entries of the US Mineral Commodity Summaries may be taken as another example. Exploration of large-scale mines takes many years. USGS changes the entries of the MCS if sufficient data and reports become available. The Moroccan data were upgraded following a report of IFDC (van Kauwenbergh, 2010) such as the Iraq data after a public presentation (Al-Bassam et al., 2012). The latter was corrected when the incompatibility of the Russian and the USGS classification was noticed. USGS data are not changed by overnight activity, nor do the PR ores disappear if downgrading takes place.

Many papers on phosphorus scarcity, such as the Edixhoven et al. paper, lack the incorporation of *the interaction of supply and demand by feedback control systems*. Factors such as long-term supply security, intergenerative justice, and the prevention of unacceptable environmental pollution ask for understanding of the supply-demand dynamics and the identification of potential barriers to getting access to sufficient phosphates in the future. Here, "[s]tatic lifetime [i.e., the R / C ratio] ... may serve as screening indicator[s] preceding early warning research" (Scholz and Wellmer, 2013, p. 11). Valid and reliable data on reserves and resources help. But when talking about these data, we have to properly acknowledge the uncertainty and the *satisficing principle* (Simon, 1955). The precision of the resources and consumption data must be good enough to draw adequate conclusions. Harmonization and transparency of the data as well as a consistent unit of recording are helpful. However, the real challenge from a sustainability-science perspective is to develop a sufficiently comprehensive system view and the capability to answer questions such as: is the current dynamic of consumption of mineral phosphorus (in agriculture, industry, diets, etc.), the increase of efficiency in production and use (as fertilizers, food additive, increasing human population), the incorporation of recycling (farms, household level, sewage plants, etc.) or

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substitution (e.g., of phosphates in technical applications) sufficient, given the geopotential for phosphorus in the long-term future (i.e., what resources may be identified, what resources may become reserves, how the costs develop, etc.) and the prospective environmental and social costs related to its use? Here, system literacy on coupled human-resources systems matters (Scholz, 2011).

7.2.2 Resources estimation is a genuine interdisciplinary and transdisciplinary issue

An interesting question is what type of science (disciplinary, basic vs. applied, interdisciplinary, transdisciplinary, etc.) is needed for resource estimation. As mentioned above, in many parts of their paper, Edixhoven et al. follow a classical exact natural science scheme that neither meets the genuine interdisciplinary nature of resources sciences nor acknowledges the socioeconomic nature of the concept of reserve. The request for fixed drilling grids for the Moroccan reserves may be taken as example. There is genuine uncertainty in any (geologic) measurement. The precision of what is economic is genuinely low, as many uncertain factors such as price development, wages development, and changes in the socioeconomic framework affect the assessment of costs. Thus, (natural) resources science is a genuine interdisciplinary field and requires modeling and conceptualization about how human systems may get access to geologic resources. This asks for taking a historic and evolutionary view of the dynamics of coupled human-environment systems (Scholz, 2011).

But even more, the knowledge from the science system is not sufficient for assessing the globally available resources. Much knowledge and data are in the possession of large mining companies, geological institutions, traders, financial institutions, etc. Transdisciplinarity has become one option by which we may efficiently relate knowledge from science and practice about the geosystem, market mechanisms, political regimes, environmental standards and impacts, and the multiple constraints on contexts that are related to mining in precompetitive discourses (Scholz et al., 2014a). The

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position by the Edixhoven et al. does not acknowledge the important role and epistemics of practice in resources management.

7.2.3 The camps of sceptics/pessimists and optimists/realists should talk to each other

In science as in society, we may find camps of optimists and pessimists/sceptics (Tilton, 1977). The pessimist mind-set that human population growth and demands increase faster than the world's resources can provide for was introduced by Thomas Malthus (1766–1843). The mixing of finiteness with staticness by neo-Malthusians may be taken as example. The opposite camp of Malthusian sceptics, sometimes labeled Cornucopians, believes that the capacity of the human mind is unlimited, and that each problem that arises, such as the problem of physical scarcity, can be overcome by technology (McKelvey, 1972).

Presumably, the truth may be found somewhere in the middle. Given the finiteness and the current level of demand, there will be a peak phosphorus level some day either as the prices become so high that consumption has to be adjusted (Scholz and Wellmer, 2013) or as humankind sophistically induces a demand driven peak by closing the anthropogenic phosphorus cycle (Scholz et al., 2014b). Phosphorus atoms are not disappearing. We suggest that resources science should focus on phosphorus flow analysis and management that encourages recycling and prevents the dissemination of phosphorus into the sea.

Scepticism may get political function: sociologists argue that (environmental) "scepticism is a tactic of an elite-driven countermovement designed to combat environmentalism, and that the successful use of this tactic has contributed to the weakening of US commitment to environmental protection" (Jacques et al., 2008, p. 349). Likewise, sceptics may consider the critique of the high Moroccan phosphate reserve estimate as a free ticket to unrestricted increase of phosphorus use and delay of recycling attempts. A critical question in this context is whether the phosphate industry may have artificially increased the Moroccan reserve data for facilitating the purchase of increas-

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ing amounts of fertilizer or for preventing policy means to promote recycling. Contrary, one may argue that an artificial increase of reserve data rather induces the idea of oversupply and thus tends to decrease phosphate prices. Here, a high estimate of the Moroccan reserves-aligned with the argument of scarcity-may cause a politically uncomfortable situation for Morocco as it may cause territorial greediness by others. When taking a critical look at these positions, these authors do not find evidence for an interest-driven overestimation of phosphate reserves by the USGS. Quite the opposite, the estimates seem to be rather conservative and are updated if new information becomes available.

7.3 Rethinking the process of assessing data on reserves and resources

Phosphorus and other nutrients may play a special role in sustainable resources management. Phosphorus is essential and dissipative by nature. Mineral phosphate reserves are finite and nonrenewable on a human time scale, and accessibility to phosphorus is essential for feeding a large world population. Thus, from the perspective of sustainability, there is a genuine interest in knowing whether and when humanity is facing supply insecurity. Wellmer and Scholz (2015) discuss the question of whether there is a right to know about the reserves, resources, and geopotential. Edixhoven et al. (p. 504) ask for a "truly independent and scientifically sound global inventory of PR deposits."

This request is facing the dilemma that – according to the rules of the global market system – the data on reserves are owned by those who generate them, and these are mostly companies who have collected the data for business purposes, given a time horizon of normally up to 50 years, only in special cases up to 100 years. Against this background, we suggest a "solidly funded international standing committee that regularly analyzes the global geopotential, focusing on the source of the future reserves and resources (Wellmer and Scholz, 2015). Such a committee may be established under the auspices of the International Union of Geosciences (IUGS) which has a significant input from governmental earth science organization or anchored initially at Euro-

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GeoSurveys (Association of the European Geological Surveys)" (Wellmer and Scholz, 2015). As mentioned above, the knowledge from practice should also be properly included here, as a transdisciplinary process is needed. The critical question, however, is whether the public is willing to pay for such an assessment of geopotential. This is a challenging and expensive issue. The principle of precautionary action (which is meaningfull if the probability of occurance is very low and the potential negatove impacts very high; see also Cameron and Abouchar, 1991) such as the right to know (Foerstel, 1999; Jasanoff, 1988) which may be referred to here are internationally intensely discussed policy and legal means that developed in the context in the field of environmental pollution and later in climate change (Jacobs, 2014). Both principles can also be applied to the field of resources if scarcity concerns call for precaution, and the present level of consumption is seen as a societally unacceptable risk for future human generations. However, such a judgment asks for comparative assessment with other environmental priorities. As the costs for this have to be covered by the public at large, this calls for a broad, international societal and political commitment. We argue that phosphorus may serve as an excellent learning case for how such a process may look and how global resource literacy may be developed.

Appendix A

Marion King Hubbert (1903–1989) wanted to overcome the simple, static snapshot view of the linear R / C ratio model for estimating future production of oil and other fuels. When facing the rapidly increasing demand and comprising the knowledge of 100 years exploration and petroleum recovery (Pratt, 1944, 1956), Hubbert, in 1956, provided (Hubbert, 1956) the remarkable prediction that oil production $P(t)$ would peak between 1965 and 1970. Factually, there was a US oil peak at that time (see Fig. 1 in this paper). Later, some scientists applied the Hubbert approach to make predictions on future phosphorus on local, regional, and global scales (Déry and Anderson, 2007). However, some of these applications did not reflect on the prerequisites that must be

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provided for an application of the Hubbert analysis. We briefly reconstruct Hubbert's modeling to help the reader understand when and why the Hubbert analysis fails. We show that the severe critiques of some predictions of global phosphorus production are not due-as Edixhoven et al. (2014) assume-to the fact that they "sourced from the Mineral Commodity Summaries," e.g., because something is thought to be wrong with the USGS data. We elaborate that the application to the global data is due to the erroneous assumption that the current estimates of reserves may be considered as an estimate of the URR.

Hubbert was facing the following prerequisites: since the late nineteenth century, US oil production/demand was strongly increasing. Growth was exponential between 1875 and 1930 (Hubbert, 1956). "Petroleum liquids" of "liquid hydrocarbons" have been superior to other fuels and a favorite chemical; there was a supply-driven market as everything produced was consumed. Based on 100 years of exploration and recovery in the US, there were good estimates (of magnitude) for the URR of 170 to 200 billion barrels of crude oil (BBO) and with 1250 BBO a very poor estimate of (magnitude) global URR. The world's proven reserves in 2013 are 1645 billion barrels (EIA, 2014). Currently, for the US, a little more than 100 BBO were produced and the proven reserves are around 30.5 BBO (EIA, 2014).

Hubbert (Hubbert, 1956) distinguished between "proved reserves" and what was recovered in the long run (in this section, we call this URR, although the URR is formally the sum of the cumulative production of the past plus what may be recovered in the future). The proved reserves, depending on fuel and region, covered about 10 to 20 % of the supposed URR. Hubbert was aware that, with oil, (a limited) number or regional exploration cycles will increase the reserves, but in 1956 Pratt's URR estimates were his reference points. We should note that he included differentiated estimates for BBO estimates for oil from oil shales and tar sands. And, most interesting, when assessing the uranium reserves, he included an estimation of the 500 Gt "phosphoria formation" for the WPF "deposits" (Hubbert, 1956).

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Later, Hubbert (Hubbert, 1959) specified the functional form of the prediction curve, and he analyzed patterns of discovery and their impact on production $P(t)$ over time, presenting the major elements of modern Hubbert analysis (Brandt, 2007). This is based on a logistic (growth) function (which in its simplest form reads $P(t) = \frac{1}{1+e^{-t}}$). This mathematical function was developed in 1844 by Pierre Verhulst to model population growth, when assuming a carrying capacity Q and a growth rate r and a population size $N = Q(t) = \int_0^t P(t)\mathrm{d}t$. In the context of resource mining, the carrying capacity $Q = Q_\infty$ mutates to URR $= Q_\infty$ and the population size $N = Q(t)$ becomes the cumulative production at time t. The population growth $P(t)$ mutates to the production at a certain time t in a logistic function with a constant exploitation parameter r. The production curve $P(t)$ is symmetrical and a derivation of the sigmoidal curve of cumulative production $Q(t)$. In some applications, such as Cordell et al. (2009), without reasoning, a Gaussian curve is taken. Naturally, this curve is symmetric (it emerges theoretically from a sum of an infinite number of small errors), but also the choice of the curve is a matter of reasoning. For instance, the symmetry of the curve was already questioned by Hubbert, stating that "probably ... the rate of decline of the" production is "less steep" than the rise (Hubbert, 1956, p. 26).

Later, the demand of knowing a URR was given up. Modern Hubbert analysis suggests that just a curve fitting of the historic logistic production curve would predict the URR and the peak of production.

The following lessons may be learned from Hubbert's analysis on US oil. The model only works if the market is a supply-driven market. This means that the amount of a commodity that is produced at any time is bought by the market, and the market may exist also with decreasing supply after the peak (e.g., by using alternative primary energy). The regulation (feedback) rule that the reserves and also the URR depend on price is neglected. Also, a multi-phasing of the production cycle by technology development has not been detected. Figure 1, for instance, shows that US oil production has been steadily increasing for about 10 years. This is due to the new technology of

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fracking, which liberates oil by hydraulic fracturing. Hubbert was well aware of oil from oil shale and tar sand deposits. But his estimates were fallacious, as he referred only to conventional extraction from shale and tar sand deposits and did not anticipate the dynamics of reserves and of the URR as a result of technological innovations.

If we look at the application of the Hubbert analysis to phosphorus, three types of applications have to be distinguished; two of them are unsubstantiated, and one provides the criteria for the Hubbert analysis.

An example of a successful application of the modern Hubbert curve analysis has been provided by Déry in relation to the guano mining on Nauru island (Déry and Anderson, 2007), once known as the smallest republic in the world. In 2007, the guano deposit had been completely stripped off after 90 years. The analysis predicted the production curve and the peak accurately when using the data from 1959 or later. The Hubbert analysis was successful, as it has been applied to a fixed deposit of guano. The economic efforts increased production until a peak after which it was more difficult to mine (the best pieces were taken), and investment efforts became less attractive. All guano, with its organic matrix, was sold immediately until the whole deposit was exploited.

A first negative example of the modern Hubbert analysis was reported by Déry and Anderson (Déry and Anderson, 2007). If you fit a logistic or Gaussian curve to the global mineral phosphorus production, you receive an estimate of a little more that 8 Gt PR-M as not yet mined URR. This is of the magnitude of factor 10 below the USGS estimate reserves (see also Vaccari and Strigul, 2011).

Cordell et al. (2009) provided an example for an incorrect Hubbert analysis with postulated known URR. As there is no estimate for a URR, she took the USGS estimate of today's reserves (i.e., of those reserves that may be mined economically with today's technology) plus the cumulative production of the past as a proxy for the URR. When using the 2010 data, she derived a peak of phosphorus production in 2033 and a decline of phosphorus production to marginal amounts of phosphate ore rock production in 50 to 100 years. When the USGS data of reserves increased from 16 Gt in 2009 to

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65 Gt in 2010 (Jasinski, 2010, 2011), Cordell et al. provided the same calculation, providing somewhat larger but completely unrealistic numbers again (Cordell et al., 2011, 4 April).

We come back to this topic at the end of this comment. Perhaps we should mention that utilizing the USGS data on reserves as an estimate of the world's URR even falls much behind the early (conservative) Club of Rome reasoning. Meadows et al. (1974, pp. 58–59), for instance, multiplied the reserves by a factor of 5 to take future discoveries into account and change them when providing a prediction on when humankind runs short of some minerals. But even this turned out to be an underestimation.

If current consumption proceeds continuously, "...one day there may be a supply-driven P production peak, ..." (Scholz and Wellmer, 2013, p. 11). This will hold true particularly if the unbroken increase in phosphate consumption continues. But we do not have enough scientific knowledge about the magnitude of the URR and the dynamics of demand and technology development to provide a robust estimate of a supply-driven peak. Rather, given the high environmental costs (Sharpley, 2014), we hope that we may face a demand-driven peak emerging from reducing consumption and making progress in closing the anthropogenic phosphorus cycle.

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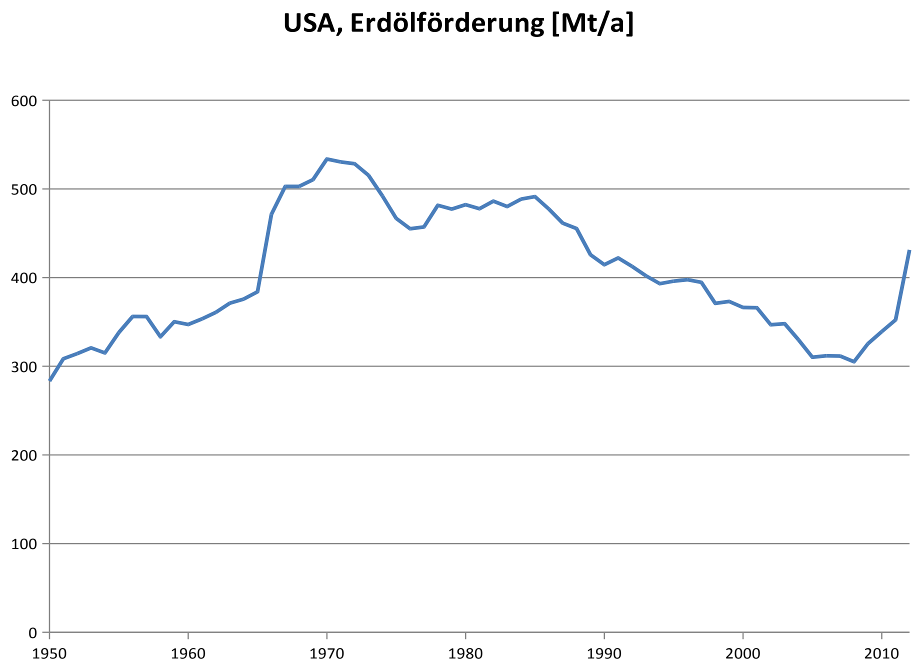

Figure 1. US oil production (Source: BGR data bank).

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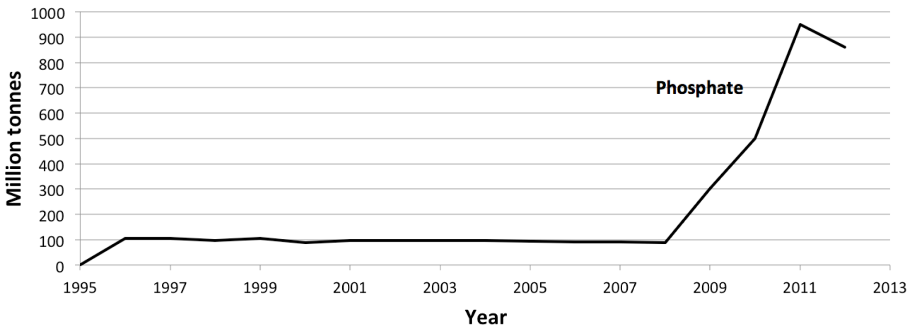

Figure 2. Australia's economic demonstrated resources of phosphate (Geoscience Australia, 2014).

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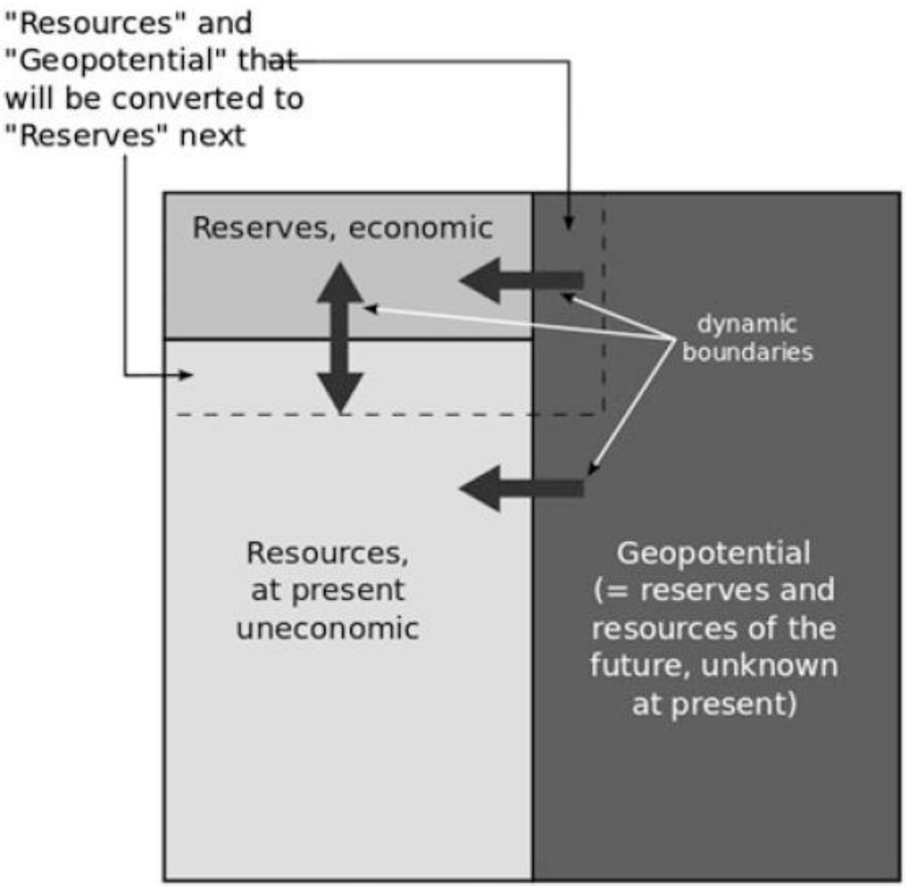

Figure 3. The total resources box (Scholz et al., 2014; modified from Wellmer, 2008).

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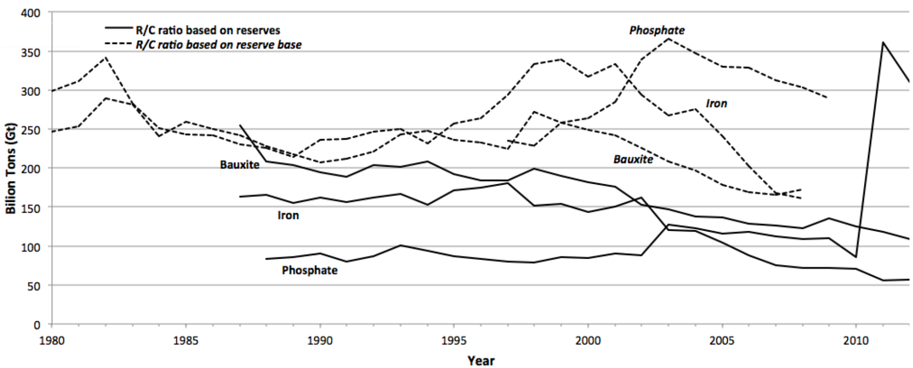

Figure 4. Comparison of the development of the R / C ratios (based on reserve base to 2008/09 and reserves) of phosphate with iron ore and bauxite (Source: USGS MCS, BGR data bank).

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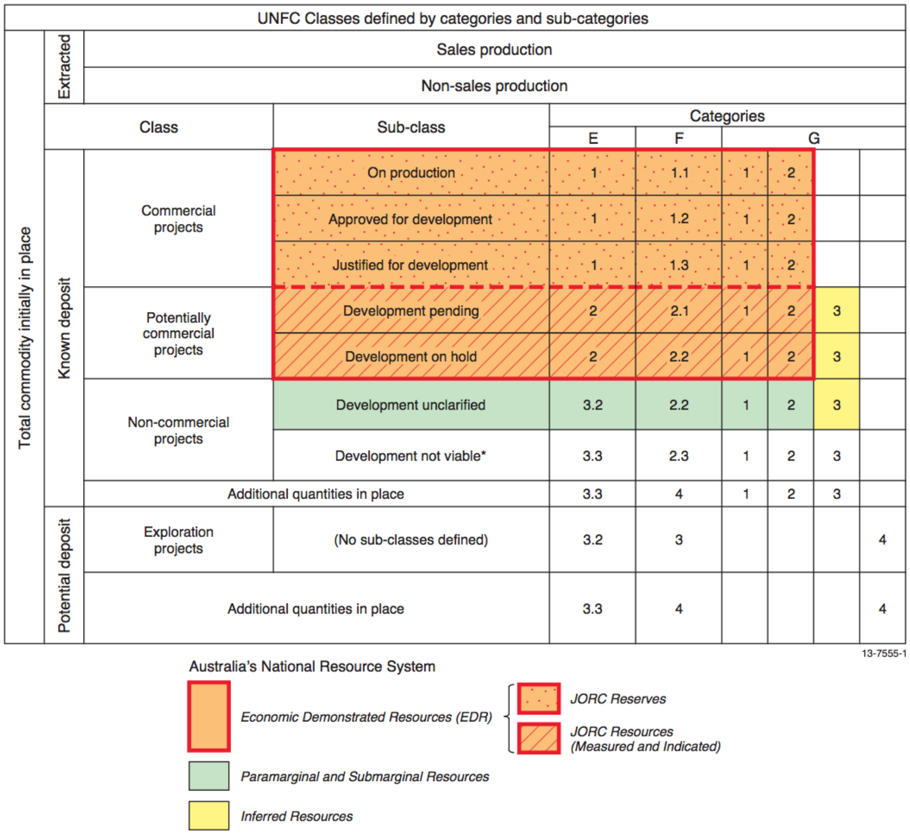

Figure 5. Correlation of Australia's national mineral resource classification system with the UNFC system (Geoscience Australia, 2014, p. 172), criteria (E) economic and social viability, (F) project status and feasibility (F), and (G) geologic knowledge.

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