

EMERGY SYNTHESIS 4: Theory and Applications of the Emergy Methodology

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Computing the Unit Emery Value of Crustal Elements

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ABSTRACT

The contributions of geologic work to human-environment systems by the concentration and transformation of minerals is an area of critical uncertainty for environmental accounting. Typically, the physical flows of mined materials into a process or a political unit are well known, but to express these flows in common emery units requires reliable estimates of their unit emery values (UEV – sej/unit, in this case, sej/g). In the past, a UEV ($1.68E9$ sej/g for the global sedimentary cycle) was determined based on an estimate of the average erosion rate of the continental crust (Odum 2000b). At this level of aggregation the implicit assumption is that flows of geologic materials are uniform with respect to work required, and no differentiation can be made among elements based on crustal abundance or ore grade. This assumption is problematic because the focal points of economic mining activities are areas of the crust with elemental concentrations greatly elevated over the crustal average, indicating geologic work requirements that are much larger than those needed for average sediment cycling. We use the assumption that UEV and concentration are linearly related to develop UEVs for 26 crustal elements based on published ore grade cutoffs (OGC). OGC values represent the enrichment ratio, ER, (ore body concentration/average crustal concentration) threshold for economically viable contemporary mining. The result is UEV values that are scaled to ore grade, so that ore bodies with OGC values of 10 have UEVs 10 times the baseline $1.68E9$ sej/g for the global land cycle. This list of 26 elements contains many, but not all, of the economically important metals. To extend this simplifying assumption to the remaining elements, we developed a simple predictive model that relates the OGC value for an element to its crustal abundance and price, both of which are widely available for all elemental commodities. This model, which captures 91% of the variability in published OGC values, was then applied to the remaining 24 crustal elements for which no OGC value was available. We view this effort as a first step in refining the way that information on geologic work is used in environmental accounting; a more intractable problem, for which we offer a possible solution, comes for mineral deposits, where composition may be more important than concentration.

INTRODUCTION

Geologic work is done to concentrate and recycle materials in the Earth's crust. This work is embodied in all processes. Human societies tap into the high quality products of geologic work to obtain the raw materials for industrial society, and ecological systems depend on geologic cycling to maintain levels of macro- and micro-nutrients. Regions of the Earth's crust that are highly concentrated in some metal or mineral represent non-renewable reserves, the extraction of which can be viewed as the spending of natural capital.

Environmental accounting (Odum 1996) seeks to integrate the work of nature and the value of natural capital into human decision making; as such, uncertainty about the contributions of geologic work to human societies is a critical knowledge gap. While it is typically straightforward to quantify the physical flows of geologic materials entering a system (see for example material flow accounting

for copper in Spatari et al. 2002), environmental accounting requires that all flows be reported in common energy units for meaningful comparison. To convert mass flows (in grams) into energy flows (in solar emjoules – sej) requires a Unit Energy Value (UEV in sej/g); in the past the average rate of crustal cycling was used to quantify a default UEV for geologic materials (Odum 2000b). The assumption that the baseline crustal cycling value of $1.68E9$ sej/g on the $15.83E24$ sej/y global energy baseline can be assigned as the default UEV for all sedimentary materials implies that all sedimentary ore deposits are of identical value (equal energy per unit mass). However, H.T. Odum's proposed 5th and 6th laws of thermodynamics (energy hierarchy and material hierarchy, respectively) generally imply that ore deposits are the result of a hierarchical process of organization and therefore elements can be expected to have a hierarchical distribution of concentrations as described below.

Metal ores populate a hierarchical distribution of enrichment vis-a-vis the mean crustal concentration. Fig. 1 shows the distribution of copper ores as a function of ore grade (% copper by mass); the y-axis (ore tonnage) is logarithmically distributed as a function of concentration, which is consistent with an energetic hierarchy. This phenomenon is consistent across crustal elements, presumably as a result of the work necessary to accomplish material concentration versus the inexorable dispersion predicted by the Second Law.

Fig 2 shows a systems schematic for how this theoretical distribution of ore body concentrations arises; ore bodies with concentrations that exceed some threshold, termed the ore grade cutoff (OGC) are economical to mine. That is, the work that has been done by geologic processes to concentrate the desired material per unit volume permits competitive investment of energy from society for extraction and further concentration (Odum 2000a). Ore bodies below this threshold require additional energy investments from society for further concentration, which is selected against in the economic system.

Naturally, the OGC value for a given crustal element is dynamic, responding to demand signals in society and technological details of extraction. However, the central premise that the Earth system has invested work that makes a given ore body useful to human society persists regardless of the operational details. In principle, it is possible for human users to concentrate materials from the Earth's crust even at the mean crustal concentration, but this demands significant energy investment (Fig. 3). Society, therefore, has self-organized to focus on those areas that permit the maximum useful material extraction for minimal resource investment. As such, enriched ore bodies storages of geologic work; from the perspective of long term sustainability, these are stores of natural capital whose concentration significantly subsidizes modern society. Future societies will draw upon ore bodies with lower OGC values that require more energy for extraction per unit mass; however, if material recycling is actively pursued, future energy demands will be lessened.

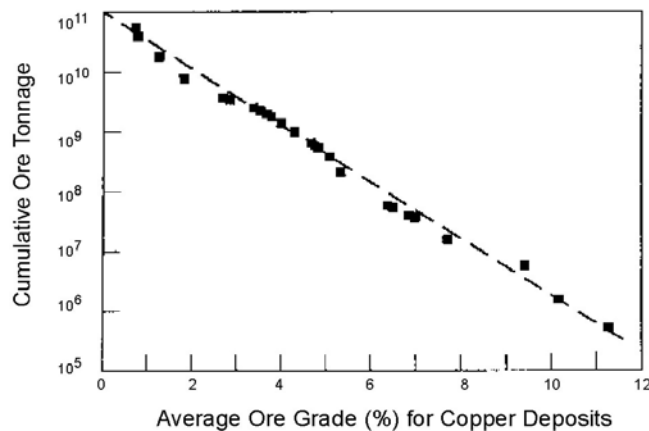


Figure 1. Lasky relation between ore grade (% copper by mass) and cumulative ore tonnage (after Kesler 1994, Fig 13.1 B).

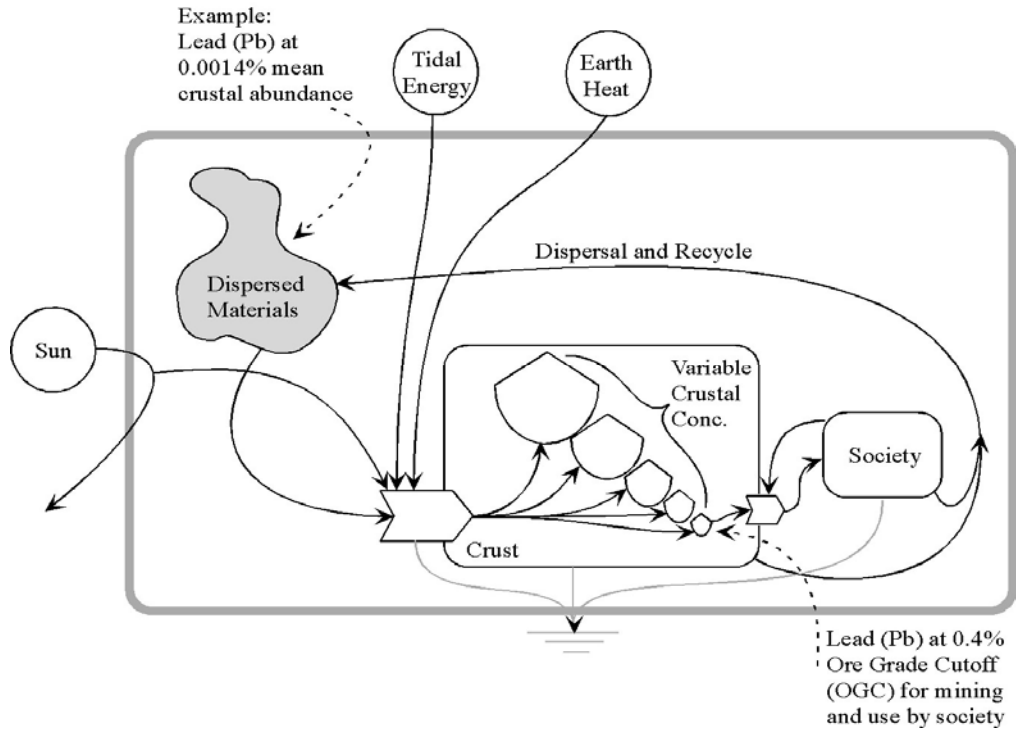


Figure 2. Concentration and dispersal of crustal elements.

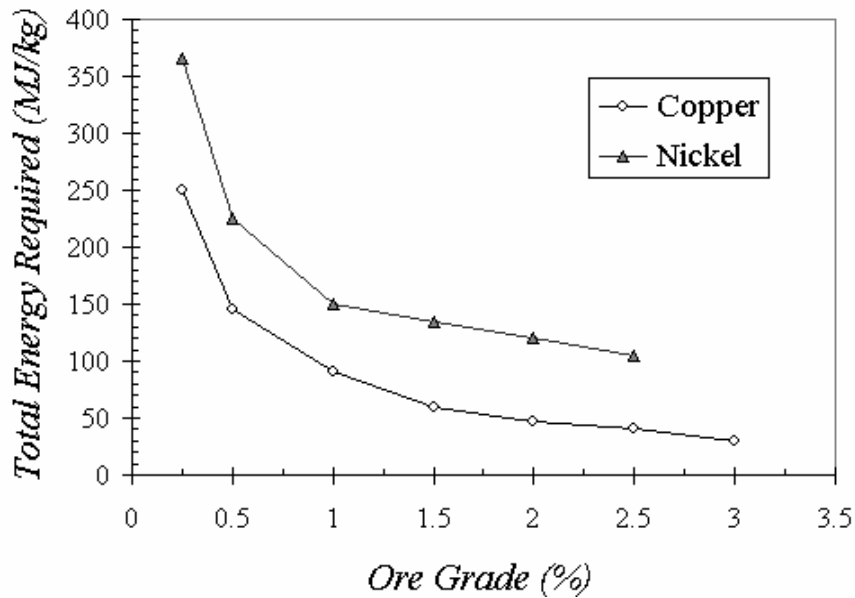


Figure 3. Plot of ore grade (% ore by mass) vs. energy invested in mining copper and nickel (after Norgate and Rankin 2000). While it is technologically possible to enrich even low-grade ores, the energy requirements make it uncompetitive. The threshold concentration for economic competitiveness (ore grade cutoff, which moves leftward over time) quantifies geologic subsidies to modern society.

METHODS

Ideally, a mechanistic model that accounts for process details in ore body formation would be developed to compute the geologic work embodied in ores of various grades. This is largely an intractable problem because of the complex processes by which ore bodies are concentrated, including magmatic separation, hydrothermal vein deposition, sedimentary sorting, and intense chemical weathering. In addition these processes frequently occur in series and in combination. Each ore body may well be viewed as unique with respect to its genesis, making generalization problematic; while it may be possible to define average UEVs for particular classes or ore bodies based on genesis, we take a 1st-order approach here of assuming that all crustal enrichment processes are thermodynamically similar. The fact that hierarchical distributional patterns hold (Fig. 1) and that there is evidence of accumulated work in ores of higher grade (Fig. 3), together indicate that the geologic concentration system can be viewed as a self-organizing network with properties not unlike those of better-studied hierarchies (Ahl and Allen 1996). For a discussion of geologic self-organizational processes from an energy systems perspective see McGrane (1998). In particular, geological work embodied in ores of different qualities can be viewed from the perspective of hierarchical unit emergy values.

In this work, we assume that the UEV for an ore body is linearly related to its concentration. This is consistent with Fig. 3, which depicts a power law association between ore grade and total energy required for extraction; were total energy (y-axis) converted to energy per mass, the relationship would be linear. Further, this is consistent with the theory outlined in Odum (2000a) on natural material hierarchies. However, regardless of the functional form of the relationship between concentration and UEV, we also centrally assume that the UEV of an ore body can be inferred from its enrichment vis-à-vis crustal background levels.

Following this assumption, we developed UEVs for 26 elements based on published ore grade cutoffs (OGC = % of the element by mass in the ore body necessary for extraction to be economical). OGC values were compiled from various sources for the year 2000 (see internet reference section). Using OGC values to determine the UEVs implies that any inferred UEV represents the lower bound for the period in question because other ore bodies being mined at that time may be higher grade. The enrichment ratio (ER) for element i is the OGC for that element divided by its average crustal concentration (CC - <http://ie.lbl.gov/chem.pdf>):

$$ER_i = OGC_i/CC_i \quad (1)$$

UEV values were computed as a function of the enrichment ratio and the global baseline UEV for land cycling:

$$UEV_i = ER_i * 1.68E9 \text{ sej/g} \rightarrow \text{Log}_{10}[UEV_i] = \text{Log}_{10}[ER_i] + 9.225 \quad (2)$$

where UEV is the unit emergy value (sej/g for this work), ER is the enrichment ratio that is the current economic minimum, and i denotes a particular element. By using the global baseline UEV for the land cycle, we assume that any element enriched above background concentrations requires more embodied work than that necessary to recycle bulk material. Further, by using the sedimentary cycle UEV only (rather than adopting the estimated UEVs for different rock types - Table 3.3 in Odum 1996), we ignore the type of rock from which element is extracted. This is done because a) the UEVs computed for different rock types (Odum 1996) assumes geologic co-production, which precludes the subsequent addition of emergy in mined products, b) the variability between rock types with respect to UEVs is relatively small (1.68 – 2.44 E9 sej/g), and c) the 1.68E9 sej/g figure is generically attributed in Odum (1996) to land cycling, which includes both erosional and uplift (isostatic and continental) work. Eq. 2 further assumes that the geologic work maintaining global land cycling and the work that enriches elements vis-à-vis background concentrations are the same qualitatively. Geologic work may concentrate elements spatially (e.g. placer deposits or hydrothermal veins), or temporally (e.g., via repeated continental recycling).

These methods are simple and straightforward, but are limited by the number of commercially extracted elements for which no OGC values were available ($n = 24$ in total, including arsenic, barium, calcium, cesium, lithium and vanadium). In order to establish approximate values for these elements,

we examined the association between other well-known properties of ores and OGC values for each element. These additional properties included the background crustal concentration (a measure of average rarity) and price (\$/ton; a measure of economic work embodied in providing that material, and partially reflective of fuels necessary to concentrate an element from ore). A simple regression model was developed relating OGC values to these more broadly known parameters. If the model effectively predicted OGC values for those elements for which OGC data were available, then it could be applied to the remaining elements to estimate their OGC values. In the absence of published OGC values, this may provide reasonable preliminary estimates of elemental UEVs despite the intrinsic uncertainty of introducing the subjective property of prices into a fundamentally biophysical calculation. Because commodity prices are constantly in flux due to market signals, we used published prices for the year 2000. Extrapolation of models using price to other periods is inappropriate.

We hasten to note here that the results of applying these methods apply only to elemental deposits. Mineral deposits, wherein composition is as important as concentration, cannot be addressed in the same way.

RESULTS

Ore-grade cutoff (OGC) values, compiled for 26 elements, are reported in Table 1 along with information on price (\$/MT), and mean crustal concentration (% by mass). Elements are ranked in order of their enrichment ratio (ER; computed as OGC:Crustal%), and consequently their UEV (specific energy; sej/g).

The list of elements for which OGC values were not available is given at the bottom of Table 1. UEVs for these elements were estimated based on the significant conditional associations between OGC (target) and price and crustal abundance (predictors) in a multiple regression model. To adjust for log-normal distributions, all variables (predictors and target) were natural \log_{10} transformed prior to developing the regression model. The model goodness-of-fit and least squares parameters are given in Table 2. We note two important features of the regression model. First, the multiple regression model using both predictors is able to reduce variance in OGC values by over 90% using the two predictors; models developed using price or mean crustal abundance alone explained less than 60% of the variance in OGC values. The residual mean squared error is 0.22 units, which corresponds to a root-mean squared error (RMSE) of 0.47; because the RMSE takes the same units as the variables (\log_{10} transformed OGC) it is more readily interpretable with respect to expected prediction errors. Second, comparing the conditional significance of each predictor (based on the t-statistic) suggests that price, which is negatively correlated with OGC values, provides more predictive information than abundance, which is positively correlated with OGC values. Both predictors are highly significant ($p < 0.001$); there was no evidence in support of an interaction term for the model.

The fit of the regression (on a log-log plot) is shown in Fig. 4. The largest residuals were observed for mercury (Hg), bismuth (Bi), beryllium (Be) and uranium (U). Residuals averaged ~ 0 , suggesting low model bias; the RMSE was 0.47 resulting in a mean error factor of 0.34 to 2.95. While this error is large, when considering the range of values over which the data vary (nearly 6 orders of magnitude), the error is comparatively small. Because UEVs are assumed linearly related with OGC values, UEV error from model prediction is similar.

Estimates of the enrichment ratio and UEV for the 24 elements for which no OGC data were available made from the fitted model are given in Table 3. Note that the inclusion of price, which is inherently volatile makes these predictions time sensitive (data were obtained for 2000); applying the same model for contemporary prices (in particular gold) may not be appropriate.

Results of model extrapolation suggest that enrichment is highly variable across elements. For example, silicon, calcium and scandium have ER values near 1, suggesting that mean crustal concentrations are sufficient for contemporary mining. Conversely, ER values for tellurium, arsenic, rhenium and ruthenium suggest that significant concentration over crustal background is necessary for extraction. The ER for rubidium (ER = 0.8) underscores the implicit difficulty of empirical extrapolation.

Table 1. Data and UEV (sej/g) estimation for 26 elements with reported ore grade cutoffs, median crustal concentration (both as a fraction of total crust), and price.

<i>Symbol</i>	<i>Element</i>	<i>Price, \$/MT</i>	<i>Crustal Fraction</i>	<i>OGC Fraction</i>	<i>ER</i>	<i>UEV</i>
Al	Aluminum	1.10E+03	8.20E-02	2.70E-01	3	5.40E+09
Fe	Iron	5.50E+01	5.60E-02	4.00E-01	7	1.20E+10
Ti	Titanium	1.30E+03	5.70E-03	2.20E-01	38	6.40E+10
Zn	Zinc	1.00E+03	7.00E-05	3.00E-03	43	7.20E+10
Cu	Copper	1.90E+03	6.00E-05	3.50E-03	58	9.80E+10
Pd	Palladium	3.10E+07	1.50E-08	1.10E-06	73	1.20E+11
Co	Cobalt	3.30E+04	2.50E-05	2.00E-03	80	1.30E+11
Cr	Chromium	6.00E+03	1.00E-04	9.20E-03	90	1.50E+11
U	Uranium	1.50E+04	2.70E-06	2.60E-04	94	1.60E+11
Ta	Tantalum	5.70E+04	2.00E-06	2.00E-04	100	1.70E+11
Ni	Nickel	7.10E+03	8.40E-05	1.00E-02	119	2.00E+11
Mn	Manganese	2.40E+02	9.50E-04	2.00E-01	211	3.50E+11
Pt	Platinum	1.90E+07	5.00E-09	1.10E-06	220	3.70E+11
Nb	Niobium	1.50E+04	2.00E-05	5.00E-03	250	4.20E+11
Ag	Silver	1.50E+05	7.50E-08	2.00E-05	267	4.50E+11
Pb	Lead	4.70E+02	1.40E-05	4.00E-03	286	4.80E+11
Au	Gold	9.00E+06	4.00E-09	1.20E-06	300	5.00E+11
Mo	Molybdenum	5.50E+03	1.20E-06	5.00E-04	417	7.00E+11
W	Tungsten	8.30E+03	1.30E-06	7.90E-04	634	1.10E+12
Be	Beryllium	6.60E+04	2.80E-06	1.80E-03	643	1.10E+12
Sn	Tin	5.10E+03	2.30E-06	2.30E-03	1000	1.70E+12
Sr	Strontium	2.70E+01	3.70E-04	4.40E-01	1186	2.00E+12
Sb	Antimony	1.50E+03	2.00E-07	5.00E-04	2500	4.20E+12
Cd	Cadmium	3.50E+02	1.50E-07	3.00E-03	20000	3.40E+13
Hg	Mercury	1.20E+04	8.50E-08	2.10E-03	25000	4.20E+13
Bi	Bismuth	7.70E+03	8.50E-09	1.60E-03	188235	3.20E+14

Elements without published OGC values: Arsenic, Bromine, Barium, Calcium, Cerium, Cesium, Gallium, Iodine, Indium, Iridium, Lithium, Magnesium, Osmium, Rubidium, Rhodium, Rhenium, Ruthenium, Scandium, Silicon, Tellurium, Thallium, Vanadium, Yttrium and Zirconium

The implications of these results are quite significant. Previously, where there were no estimates of global UEVs for mined products, the mean specific emery for crustal cycling was used (1.68E+09 sej/g). We note that elements listed in Tables 1 and 3 have a specific emery greater than this value, suggesting as expected that the ore bodies that form the material basis for modern industrial society have required enormous past geologic work. We also note that if the baseline UEV were changed to reflect estimates for different rock types, the estimated UEVs for each element would also change. We would anticipate these changes to be comparatively small.

Table 2. Regression statistics for OGC prediction model based on crustal abundance and price. Note that the target variable (OGC value) and predictors were \log_{10} transformed prior to analysis to satisfy assumptions of normality.

Predictor	Coefficient	Std. Error	t-statistic	P-value
Constant	3.495	0.651	5.37	<0.001
Ln (Abundance)	0.363	0.065	5.6	<0.001
Ln (Price)	-0.604	0.087	-6.91	<0.001

Source	DF	SS	MS	F	P
Regression	2	57.84	28.92	129.2	<0.001
Residual Error	23	5.14	0.223		
Total	25	62.98			

n = 26, S = 0.473, $R^2 = 0.92$

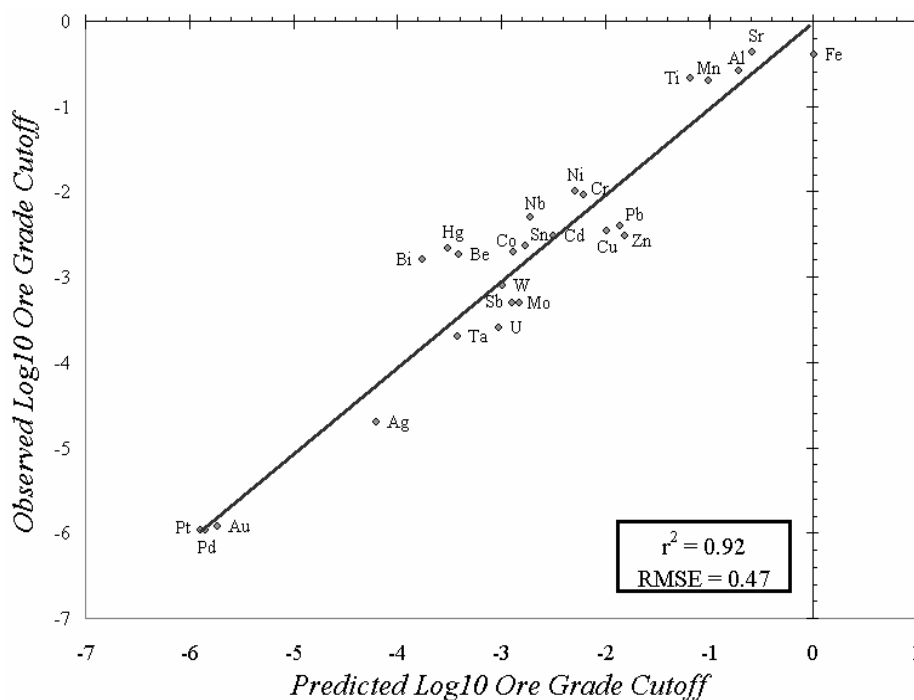


Figure 4. Observed vs. Predicted ore grade cutoff (OGC) from regression model described in Table 2. Root mean squared error (RMSE) = 0.47.

Fundamentally, the work of the earth system in concentrating the raw materials for human use has been previously underestimated because of the additional energy required to concentrate elements to the OGC. Table 4 offers a preliminary glimpse of the effects of this change, summarizing the metal production statistics for 138 nations compiled from the United States Geological Survey (USGS) and British Geological Survey (BGS). These data were compiled for the National Environmental Accounting Database (NEAD – Sweeney et al. 2006; *this volume*) circa 2000.

Table 3. Data and UEV estimation for 26 elements without reported ore grade cutoffs. UEVs are predicted from, price and mean crustal concentration.

<i>Symbol</i>	<i>Element</i>	<i>Price, \$/MT</i>	<i>Crustal Fraction</i>	<i>Est. OGC Fraction</i>	<i>Est. ER</i>	<i>Est. UEV</i>
As	Arsenic	7.72E+02	1.80E-06	4.89E-03	2716.7	4.56E+12
Ba	Barium	1.40E+01	4.25E-04	4.02E-01	945.3	1.59E+12
Br	Bromine	9.00E+02	2.40E-06	4.94E-03	2058.3	3.46E+12
Ca	Calcium	4.84E+03	4.15E-02	6.25E-02	1.5	2.53E+09
Ce	Cerium	3.50E+05	6.65E-05	4.50E-04	6.8	1.14E+10
Cs	Caesium	9.56E+06	3.00E-06	2.00E-05	6.7	1.12E+10
Ga	Gallium	6.40E+05	1.90E-05	2.00E-04	10.5	1.77E+10
I	Iodine	1.44E+05	4.50E-07	1.30E-04	288.9	4.85E+11
In	Indium	3.20E+05	2.50E-07	6.00E-05	240.0	4.03E+11
Ir	Iridium	1.28E+07	1.00E-09	9.00E-07	900.0	1.51E+12
Li	Lithium	8.50E+02	2.00E-05	1.10E-02	552.0	9.27E+11
Mg	Magnesium	1.95E+03	2.33E-02	8.52E-02	3.7	6.14E+09
Os	Osmium	1.12E+07	1.50E-09	1.15E-06	766.7	1.29E+12
Rb	Rubidium	9.98E+06	9.00E-05	7.00E-05	0.8	1.31E+09
Re	Rhenium	1.00E+06	7.00E-10	3.72E-06	5314.4	8.93E+12
Rh	Rhodium	1.92E+07	1.00E-09	7.15E-07	715.4	1.20E+12
Ru	Ruthenium	1.50E+06	1.00E-09	3.31E-06	3314.8	5.57E+12
Sc	Scandium	2.00E+07	2.20E-05	3.00E-05	1.4	2.29E+09
Si	Silicon	1.10E+03	2.82E-01	3.03E-01	1.1	1.80E+09
Te	Tellurium	4.40E+04	1.00E-09	3.00E-05	30000.0	5.04E+13
Tl	Thallium	1.10E+06	8.50E-07	5.00E-05	58.8	9.88E+10
V	Vanadium	8.80E+03	1.20E-04	5.16E-03	43.0	7.22E+10
Y	Yttrium	5.00E+05	3.30E-05	2.80E-04	8.5	1.43E+10
Zr	Zirconium	2.50E+04	1.65E-04	3.12E-03	18.9	3.18E+10

Note: The following elements have no price data, and therefore no UEV estimate: Argon, Boron, Carbon, Chlorine, Fluorine, Germanium, Potassium, Krypton, Lanthanum, Nitrogen, Sodium, Neon, Oxygen, Phosphorus, Sulfur, Selenium, Thorium, Xenon

The simplest comparison is between the total emery from mined elements for national production data using the two different UEVs. The results suggest that the mean difference in flows for all elements is over one order of magnitude ($2.18\text{E}+24$ sej/yr vs. $2.40\text{E}+25$ sej/yr). While these statistics are not global production data, they can be compared approximately with previous global inventories (e.g. Brown and Ulgiati 1999). We infer that total global use, which includes mined materials rises from $5.03\text{E}+25$ sej/yr to $1.07\text{E}+26$ sej/yr largely on the basis of changes in the computation of geologic inputs. The fraction of total global emery use derived from mined metals rises from 4.35% to 22.40% when these new UEVs are employed.

Table 4. Comparison of total emery flow from the mining of elements for 138 nations using UEVs computed in this work vs. previous methods.

Commodity	Symbol	Global Prod. (MT) [†]	New UEV (sej/g)	Previous Emery Est. (sej) [‡]	New Emery Est. (sej)
Iron	Fe	1.09E+09	1.19E+10	1.83E+24	1.30E+25
Manganese	Mn	8.36E+06	3.54E+11	1.40E+22	2.96E+24
Lead	Pb	3.06E+06	4.80E+11	5.14E+21	1.47E+24
Copper	Cu	1.32E+07	9.80E+10	2.22E+22	1.30E+24
Chromium	Cr	6.77E+06	1.52E+11	1.14E+22	1.03E+24
Aluminum	Al	1.39E+08	5.41E+09	2.34E+23	7.52E+23
Titanium	Ti	1.39E+06	6.42E+10	2.33E+21	6.67E+23
Zinc	Zn	8.82E+06	7.20E+10	1.48E+22	6.35E+23
Antimony	Sb	1.26E+05	4.20E+12	2.12E+20	5.29E+23
Tin	Sn	2.47E+05	1.68E+12	4.15E+20	4.15E+23
Strontium	Sr	1.52E+05	1.99E+12	2.55E+20	3.03E+23
Nickel	Ni	1.25E+06	2.00E+11	2.10E+21	2.50E+23
Arsenic	As	4.20E+04	4.56E+12	7.05E+19	1.92E+23
Magnesium	Mg	2.02E+07	6.14E+09	3.39E+22	1.24E+23
Iodine	I	2.19E+05	4.85E+11	3.68E+20	1.06E+23
Molybdenum	Mo	1.36E+05	7.00E+11	2.28E+20	9.50E+22
Mercury	Hg	1.39E+03	4.20E+13	2.33E+18	5.82E+22
Tungsten	W	3.04E+04	1.07E+12	5.11E+19	3.24E+22
Zirconium	Zr	1.00E+06	3.18E+10	1.68E+21	3.18E+22
Uranium	U	1.11E+05	1.59E+11	1.86E+20	1.76E+22
Tantalum/Niobium	Ta/Nb	7.71E+04	1.68E+11	1.29E+20	1.29E+22
Lithium	Li	1.21E+04	9.27E+11	2.03E+19	1.12E+22
Silver	Ag	2.14E+04	4.48E+11	3.59E+19	9.57E+21
Cobalt	Co	3.40E+04	1.34E+11	5.72E+19	4.57E+21
Vanadium	V	3.95E+04	7.22E+10	6.64E+19	2.86E+21
Gold	Au	2.56E+03	5.04E+11	4.30E+18	1.29E+21
Rare Earth Metals	Various	8.32E+04	~1.4E+10	1.40E+20	1.16E+21
Platinum	Pt	2.12E+02	3.70E+11	3.56E+17	7.82E+19
Palladium	Pd	2.38E+02	1.23E+11	4.01E+17	2.94E+19
METAL TOTAL		1.30E+09		2.18E+24	2.40E+25
GLOBAL TOTAL				5.03E+25 [§]	1.07E+26 [¶]
% of Total Use				4.35%	22.40%

[†] - data for Sb, Cr, Li, Mn, Sr from USGS - <http://minerals.usgs.gov/minerals/pubs/commodity/>; all other data from British Geological Survey at http://www.mineralsuk.com/free_downloads.html#WMP

[‡] - Assuming standard UEV of 1.68E9 sej/g

[§] - Brown and Ulgiati 1999

[¶] - Sweeney et al. 2006; this volume

DISCUSSION

Environmental accounting (EA) requires systems-scale information about the past work required for all potential process inputs. Because so many products integrate geological stocks in production, the absence of accurate unit emery values for mined materials represents a major impediment to the implementation of comprehensive EA analyses. Previously, geologic work was generally internalized into system energetics based on the assumption that all geologic products could be valued equally at the level required for average crustal recycling. However, because ore bodies represent a concentration gradient vis-à-vis background levels, this assumption is problematic. That is, it is acknowledged in other areas that concentration gradients represent embodied work combating Second Law dispersal (Brandt-Williams 2001). This work represents a further step towards a comprehensive framework for analyzing geologic work in economic-environmental systems.

Results of this study predict that different elements have widely variable UEVs, varying over 5 orders of magnitude. The lowest UEVs were observed for those elements that require very little enrichment over background levels to be of use to society (Al, Fe, and Ti). These metals represent the key building blocks of industrial society. Other elements, though important in many specific processes, are both less widely used and significantly less abundant. The highest UEVs are, surprisingly, not for the rare earth metals (platinoids) or gold but for Hg, Bi and Cd which have high OGC values in addition to being relatively scarce in the crust.

UEVs are needed for all material inputs to industrial society. There are two limitations of our ore grade cutoff (OGC) method for this broad purpose. The first, which we address empirically in this work, is that there are a significant number of elements for which published OGC values are unavailable. Because the economics of mining are largely generalizable, OGC values are expected to exist, and efforts are ongoing to identify sources of this information for the 24 elements for which no data were available. Our temporary solution to this problem was to develop a predictive relationship between the required OGC value and ancillary information, specifically mean crustal concentration (%) and price. While there are clear drawbacks to the selection of price as a predictor of UEVs, we proceeded with the analysis for two reasons. First and most clearly, the strong association between price and OGC (and therefore UEV) is clearly demonstrable and useful for this provisional purpose. Second, OGC values are fundamentally as subjective as prices. In fact, OGC values integrate information about scarcity and utility in much the same way that price does, making the strong relationship observed fully expected. The determination of enrichment ratios is the main objective of this method, and the OGC values simply quantify the minimum viable enrichment for mined ores under current market conditions; we hasten to point out that many mines may extract ores at higher enrichment ratios. If we accept that current market conditions allow us to specify the OGC for an element extracted from the crust, then current prices should suffice to estimate the degree of enrichment required. Regardless, we view this inferential process as provisional until better OGC values can be obtained.

A second limitation of the OGC approach is that many mined materials are not elemental ores, but minerals. In this case, composition affects desirability as well as concentration. The implicit assumption that there are energetic pathways that concentrate elements against background levels, and that the work embodied in these processes can be inferred from the concentration of the output ore body, cannot be generalized simply to minerals.

One solution to this problem is to compute the exergy, which takes accounts for the available chemical energy for the various ore bodies (Martinez 2006) and compare to the estimated UEVs. If, as expected, exergy and UEV are linearly related for metal ores, then we may extrapolate that association to minerals based on exergetic computations for the various mineral deposits.

Perhaps the most significant assumption in this work is that UEVs are linearly related to ore body enrichment from background concentrations. This assumption of linearity results in the condition where the emery embodied in a given mass of ore (the mixture) goes up with the square of

the mass of the (pure) element of interest in that ore. A non-linear association with concentration may be warranted based on the energy necessary to concentrate metals for low grade ores (e.g. Fig. 3).

The implications of changing the manner in which the emergy of mined elements are valued are significant. Overall emergy estimates for mined production of crustal elements only (that is, excluding mineral extraction) grows by a factor of more than 2 *vis-à-vis* previous efforts to quantify global mined flows. This increase in the emergy value of geologic deposits is important for underscoring the material basis of modern industrial society and it is a cautionary tale regarding the strength of the link between society's energy metabolism and its material use.

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Data	Source
Mean Crust %	http://ie.lbl.gov/chem/pdf
Antimony	http://www.nrcan.gc.ca/mms/pdf/explor/2004/2.04-e.pdf
Aluminium	http://minerals.usgs.gov/minerals/pubs/commodity/bauxite/bauxmyb01.pdf
Arsenic	http://minerals.usgs.gov/minerals/pubs/commodity/arsenic/160301.pdf
Barium	http://minerals.usgs.gov/minerals/pubs/commodity/barite/080301.pdf
Beryllium	http://www.webmineral.com/chem/Chem-Be.shtml
Beryllium	http://minerals.usgs.gov/minerals/pubs/commodity/beryllium/100301.pdf
Bismuth	http://minerals.usgs.gov/minerals/pubs/commodity/bismuth/bimis4q04.pdf
Bromine	http://minerals.usgs.gov/minerals/pubs/commodity/bromine/130301.pdf
Cadmium	http://minerals.usgs.gov/minerals/pubs/commodity/cadmium/cdmyb2001.pdf
Cesium	http://minerals.usgs.gov/minerals/pubs/commodity/cesium/200301.pdf
Chromium	http://www.chromium-asoc.com/publications/directory/pdf/CRORE/omc_ltd.pdf
Chromium	http://minerals.usgs.gov/minerals/pubs/commodity/chromium/chromyb01.pdf
Cobalt	http://minerals.usgs.gov/minerals/pubs/commodity/cobalt/210400.pdf
Copper	http://www.em.gov.bc.ca/cf/minfile/search/search.cfm?mode=capbib&minfilno=093E++037
Copper	http://minerals.usgs.gov/minerals/pubs/commodity/copper/coppmyb01.pdf
Erbium	http://www.scescape.net/~woods/elements/erbium.html
Europium	http://www.radiochemistry.org/periodictable/elements/63.html
Gallium	http://minerals.usgs.gov/minerals/pubs/commodity/gallium/460301.pdf
Gold	http://www.minecost.com/data1st.htm
Iodine	http://minerals.usgs.gov/minerals/pubs/commodity/iodine/770301.pdf
Iron	http://www.pir.sa.gov.au/pages/minerals/commodity/iron_ore.htm:sectID=245&tempID=7
Lead	www.nwtgeoscience.ca/normin/cutoffs.htm
Lead	http://www.eos.ubc.ca/courses/eosc110/fletcher/iglist.html
Lithium	http://www.webmineral.com/chem/Chem-Li.shtml
Lithium	http://minerals.usgs.gov/minerals/pubs/commodity/lithium/450301.pdf
Magnesium	http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/400301.pdf
Manganese	http://minerals.usgs.gov/minerals/pubs/commodity/manganese/420302.pdf
Mercury	http://minerals.usgs.gov/minerals/pubs/commodity/mercury/hgmyb2001.pdf
Molybdenum	http://www.em.gov.bc.ca/cf/minfile/search/search.cfm?mode=capbib&minfilno=093E++037
Molybdenum	http://www.em.gov.bc.ca/cf/minfile/search/search.cfm?mode=capbib&minfilno=093B++012
Nickel	http://minerals.usgs.gov/minerals/pubs/commodity/nickel/500400.pdf
Niobium	http://www.webmineral.com/data/Ferrocolumbite.shtml
Palladium	http://www.platinum.matthey.com/uploaded_files/publications/Cawthorn.pdf
Platinum	http://www.platinum.matthey.com/uploaded_files/publications/Cawthorn.pdf
Rubidium	http://minerals.usgs.gov/minerals/pubs/commodity/cesium/201301.pdf
Silver	http://www.macmin.com.au/Sep00quarter.html
Silver	http://www.minecost.com/data1st.htm
Strontium	http://minerals.usgs.gov/minerals/pubs/commodity/strontium/srmyb01.pdf
Strontium	http://minerals.usgs.gov/minerals/pubs/commodity/strontium/850301.pdf
Tantalum	http://www.webmineral.com/data/Pyrochlore.shtml
Tantalum	http://www.mining-australia.com/nib-october01.html
Titanium	http://minerals.usgs.gov/minerals/pubs/commodity/titanium/titanmyb02.pdf
Titanium	http://www.ngdir.ir/Plants/PlantsList.asp?PStateCode=13
Tungsten	http://www.nwtgeoscience.ca/normin/cutoffs.htm
Zinc	www.nwtgeoscience.ca/normin/cutoffs.htm