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GLOBAL AND REGIONAL GEOCHEMICAL INDEXES OF PRODUCTION OF CHEMICAL ELEMENTS

ABSTRACT. This paper presents a geochemical assessment of the primary involvement of chemical elements in technogenesis in the world and individual countries. In order to compare the intensity of production of various chemical elements in different countries, the authors have introduced a number of new terms and parameters. The new term is "abstract rock" (AR) – an elemental equivalent, whose average composition corresponds to the average chemical composition of the upper continental crust. The new parameters are: "*conditional technophility of an element*" (T_Y), "*specific technophility*" (T_{YN}) "*regional conditional technophility*" (T_{YR}), "*specific regional technophility*" (T_N), and "*density of regional conditional technophility*" (T_S). T_Y equals to the tons of AR per year necessary for the production of the current level of the element. T_Y of different elements has been estimated for 2008–2010. The highest T_Y values are associated with C, S, N, Ra, and Au. T_Y of many micro- and ultramicroelements is of the order of $n \cdot 10^{11}$t. T_{YN} reflects the volume of AR per the world's capita. T_{YN} changes from the 1960s to 2010 indicates that the Earth's population is growing much faster than its demand for many chemical elements. T_{YR}, T_N, and T_S were used for the integrated assessment of technogenesis at the regional scale; they reflect the intensity of the technogenesis process at the level of individual countries and allow comparing countries with different levels of elements production, population, and areas. The T_N and T_S levels of the leaders in extraction of natural resources are below these values in other countries due to the large territories (Russia, USA, Canada, Australia, Saudi Arabia, Kazakhstan, Argentina, Bolivia, Venezuela, Colombia, Zambia, Mali, Libya, Mongolia, and Sudan), to the large population (Indonesia, Vietnam, the Philippines, Bangladesh, Nigeria), or to both high spatial and demographic dimensions (India, Brazil, France, Egypt, Thailand, Pakistan, Algeria, Tanzania, Congo (Kinshasa), Malaysia, and Morocco).

KEY WORDS: technogenesis, tehnophility, elements production, elemental equivalent.

INTRODUCTION

Extraction of chemical elements from different layers of the Earth – the lithosphere, hydrosphere, and atmosphere, their controlled and spontaneous incorporation in a man-made migration, which currently involves almost the entire globe, creation of new artificial and "alien" to the biosphere compounds, global anthropogenic scattering, and intense local concentration of elements in the cities and near deposits of natural resources generate increasingly more clearly manifested geochemical differences between different terrestrial macroregions, countries, and their parts. In the last quarter of the XXth century, N.F. Glazovskiy has formulated the idea of a new direction in environmental geochemistry – geochemical regional geography [Glazovskiy, 1976].

The methods of comparison of countries by the intensity of certain aspects of technogenesis[1] represent a ranking system with a large number of characteristics and a general principle of descending or ascending ranking. These methods include: the "geographical" method that primarily considers the common physical and economic-geographical characteristics of countries: area, population size and density, GDP, etc. [Tikunov & Tsapuk, 1999]; the "matter-energy" method that considers the levels of production of energy, mineral and other resources, and goods [Mineral..., 2012; Key world..., 2012]; the "geochemical" method that considers identification of the intensity of technogenic migration of elements and representation of the flows of goods as the flows of chemical elements between countries, regions, cities, etc. [Glazovskiy, 1976]; and the "environmental" method that involves calculation of a set of coefficients and indices. The latter includes the following approaches: "environmental price" utilizing basic indicators (GDP, gross domestic savings, net domestic product), adjusted for the valuation of natural resource depletion and environmental damage, and natural capital, e.g., genuine savings index (GSI), environmentally adjusted net domestic product (EDP), etc. [Bцhringer & Jochem, 2007; Bityukova & Kirillov, 2011]; "sustainable development" that includes the quality of life and environmental indicators – human development index (HDI), environmental sustainability index (ESI), environmental performance index (EPI), ecological footprint (EF), living planet index (LPI), absolute and proportional composite environmental rankings (aENV, pENV), etc. [Esty et al., 2005; Bцhringer & Jochem, 2007; Bradshaw et al., 2010; Bityukova & Kirillov, 2011]; "technogenic impact" that involves the grouping of countries, regions, and cities by the intensity of impact on the individual components of the environment, e.g., on the atmospheric air, with assessment of the total emissions from industry and vehicles [Bityukova et al., 2012] and emissions of individual elements or compounds, i.e., heavy metals, CO_2, CH_4, SO_2, NH_3, etc. [Pacyna & Pacyna, 2001; Nriagu & Pacyna, 1988; Denier van der Gon et al., 2009; Revised.., 2012; Bityukova, Kasimov, 2012]; or the integrated assessment of the anthropogenic impact considering several components simultaneously [Bityukova, 2010].

The "emission", "matter-energy," and "geochemical" approaches are the best methods for the evaluation of the intensity of technogenesis in the world and individual countries, because they allow identifying groups of countries with close parameters of direct and indirect impact on the environment. However, to date, these approaches have not utilized integral parameters.

In order to assess the involvement of chemical elements in technogenesis at the global and regional scales, it is necessary to know the value of the primary technogenic mobilization of the elements of the Earth's interior (extraction of different types of natural resources), abundance of elements (which directly influences the potential of their inclusion in the technogenic migration [average composition of the upper continental crust]), and geographical parameters that influence the magnitude of elements production (spatial and demographic dimensions of countries). Geology and endowment of mineral resources determine the distribution of the chemical elements production in different countries. But these factors are not discussed in the paper, because we focused on searching geochemical indexes which allow to compare countries with different levels of elements production, population, and areas.

Technophility (*T*) is an important notion for understanding the basic trends in the intensity of chemical elements extraction from the Earth's interior and their use in techcnogenesis. *T* represents the ratio of the annual primary production of an element in tons to its average concentrations in the Earth's crust [Perel'man, 1975]. *T* is an informational coefficient that reflects the level of chemical elements production in different phases of the technogenic development of society. Some elements are extracted by mankind proportionately to their average content in the Earth's crust (Cd, Hg, U, Mo, Ti, and Zr), while for others, such dependency is lacking.

T of various chemical elements varies over time [Kasimov & Vlasov, 2012] and depends on the increasing or decreasing intensity of elements production and corrections in the previously calculated average composition of the Earth's crust. The work presented herein improves the earlier calculations of *T* with the new data on the production of Os, Sc, Rb, some platinum group metals, noble gases, rare earths, and information on the elements production in Africa and Central America [Kasimov & Vlasov, 2012]. The authors have calculated the mean values of the elements production for the three years (2008–2010), accounted for the impact of the global economic crisis on the mining industry, and used the information on the production of elements in almost all countries of the world and the latest data on the average composition of the upper continental crust.

MATERIALS AND METHODS

The production values of most chemical elements and their compounds were derived from the annual reports of the U.S. Geological Survey (USGS) averaged over 2008–2010 [Mineral ..., 2012; International minerals .., 2012]. In the absence of data for 2010, the information for 2007 averaged over 2007–2009 was used. The production levels of elements in the 1960s were obtained from [Perel'man, 1975], in the 1980s – from [Emsley, 1991], in the late 1990s and early 2000s – from [Mineral ..., 2012; Butterman et al., 2003, 2004]. The production of some elements was calculated from the values of production of the essential minerals.

Thus, the USGS data state that zirconium concentrates contain up to 49,8% Zr. They are also the only source of Hf – about 2% of the mass [Mineral ..., 2012]. Extracted spodumene $LiAl(Si_2O_6)$ contains 3,73% Li, lepidolite – 3,1–6,0% Li_2O. The oxide content of 40% was used to calculate the Ta_2O_5 and Nb_2O_5 contents from tantalite and columbite, respectively. Djalmaite can contain up to 15% UO_3. The mass of rare earth elements produced was calculated from their average content in the main ore mineral – bastnaesite: 49% Ce, 34% La, 13% Nd, 4% Pr, and 0,1% for other individual elements in this group [Haxel et al., 2002; Yang et al., 2009].

Data on the production of fossil fuels (coal, oil, and natural gas) were obtained from [International energy ..., 2012]. Barrels to tons conversion was done assuming a coefficient of 0,1364 and the density of natural gas of 0,765 kg/m^3. After reducing the data on fossil fuels production to the common unit of measure (tons per year), the mass of CO_2 and C content were calculated using the average calorific value coefficients and emission factors: for oil – 42,5 TJ/kt (i.e., TJ per thousands of tons) and 20 t C/TJ, respectively; for coal – 20 TJ/kt and 25,8 20 t C/TJ; and for natural gas – 43 TJ/kt and 15,3 t C/TJ [Revised ..., 2012].

Information on the production of Xe, Kr, Ne, Ar, Os, Sc, Po, Ac, Pa, Th, Cs, and Rb was obtained from [The world market.., 2012; Environmental, chemistry.., 2012; Butterman et al., 2003, 2004]; the data on the population size and area of individual countries and of the world as a whole – from [The world factbook, 2012]; and the data on the population of the Earth at different times of the last century – from [Kapitza, 1999].

The authors took into account only the main sources of production of elements; although many natural resources (sand, limestone) contain trace elements whose masses are generally very high, they are only "potentially" involved in technogenesis and are only "associated" with the production, without being its primary goal.

In Russia, the average contents of the elements in the Earth's crust calculated by A.P. Vinogradov [Vinogradov, 1962] are often used, whereas only its upper part is a reservoir of natural resources used by mankind and the main source of most of the chemical elements involved in technogenesis. Therefore, when estimating the intensity of technogenesis, as well as in environmental and geochemical studies, it is feasible to apply the average composition of the upper continental crust calculated from the weighted averages of the chemical composition of rocks exposed at the Earth's surface [Clarke, 1889], or the average composition of fine-grained clastic sedimentary rocks, glacial deposits, or glacial loess [Goldschmidt, 1933]. R.L. Rudnick and S. Gao [2003] calculated average composition of the upper crust using both methods separately for macro- and microelements according to their solubility, correlation with La, and relations with other elements, for example, Rb/Cs.

The estimates of [Grigoriev, 2009] for some elements are very different from those of [Rudnick & Gao, 2003]; the concentrations are higher for S – 23 times, for Br and Cd – 7 times, for Cl – 4 times, for Au –3 times, and for B, Ca, Se, Ag, Sn, Sb, Gd, Ho, Lu, Ta, and Bi – 1,5–2 times; the concentrations for I is 3 times lower. The difference in the average concentrations in the upper continental crust of 1,5–3 times is not that significant for the assessments of the technogenesis intensity; therefore, this work relied on the average composition of the upper continental crust of R.L. Rudnick & S. Gao due to a larger list of elements included in their estimates. The average composition of the upper continental crust of [Grigoriev, 2009] were used for S, Br, Cd, and Cl.

For inert gases, Po, Rn, Ra, Ac, Pa, Rh, and Te, the concentrations in the upper continental crust have not been estimated; therefore, this paper used the average concentrations in Earth's crust in general [CRC Practical Handbook, 1989; Greenwood & Earnshaw, 1997; Vinogradov, 1962].

RESULTS AND DISCUSSION

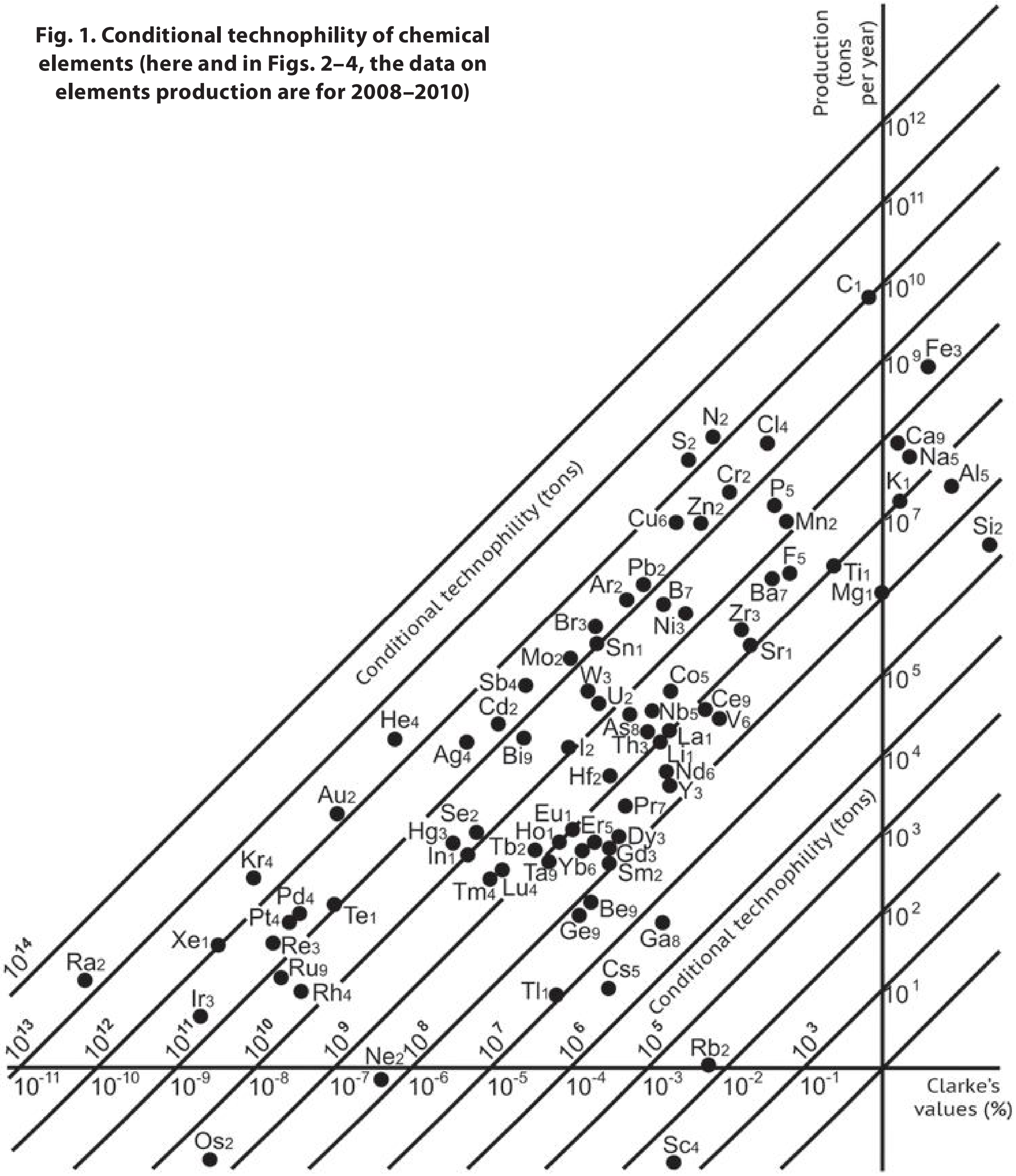
Global estimates of the intensity of technogenesis

If technophility is multiplied by 100, then it has a physical meaning: the unit of T corresponds to the volume of extracted "abstract rock" (AR) (in tons) required for production of X grams of the element, where X is the value of the average concentration of element in the upper continental crust in g/t. In this case, AR corresponds to rock whose chemical composition equals to the average chemical composition of the upper continental crust. Hereafter, the authors are using the term "conditional technophility" (T_Y) to indicate the volume of extracted AR necessary for the production of a chemical element corresponding to its current level. The high level of contrast (from $n \cdot 10^3$ to $n \cdot 10^{13}$t) and temporal variability (large differences in production volume over time) of T_Y for different elements allows using this parameter as one of the general indicators of technogenesis.

The assessment of the total production of different types of natural resources, varying in composition, represents a problem in analysis of a number of aspects of technogenesis. For fossil fuels, this problem may be solved by converting the mass of fuel to an equivalent amount of CO_2 that can be released into the environment by burning, or by using the energy equivalent – by converting it to tons of oil equivalent [Revised ..., 2012]. The term "abstract rock" proposed herein is similar to the term "oil equivalent" and can be used for comparison of intensity of production of different chemical elements and for their overall accounting, i.e., it represents an elemental equivalent. Calculation of the sum of T_Y of chemical elements provides for assessment of their integrated involvement in technogenesis.

At the end of the first decade of the XXIst century, the largest T_Y was associated with C, S, N, Ra, Au, Xe, Kr, and He (Fig. 1). High T_Y of inert gases can be explained by the fact

Fig. 1. Conditional technophility of chemical elements (here and in Figs. 2–4, the data on elements production are for 2008–2010)



that the main source of their production is not the upper continental crust, but the atmosphere; therefore, it is more feasible to use the average composition of the atmospheric air. Under this approach, their T_Y values decrease by several times: about 100 times for He, while for Kr, Xe, Ar, and Ne – by 10000 times. Therefore, the data on the production of inert gases was not considered in the regional assessments of technogenesis. T_Y of some elements with very low average concentrations in the upper continental crust are not shown in Fig. 1: for Po it equals to $5 \cdot 10^{11}$t, for Ac – $2 \cdot 10^{9}$t and for Pa – $9 \cdot 10^{8}$t. T_Y of rare earth elements is $9 \cdot 10^{8}$t and varies from $4 \cdot 10^{9}$t for Lu to $2 \cdot 10^{8}$t for Sm.

Many micro-and ultramicroelements – Cr, Zn, Cu, Pb, Br, Sn, Mo, Sb, Cd, Ag, and some platinum group elements used for the production of various industrial products, spare parts, and car fuel, have T_Y of $n \cdot 10^{11}$t. The minimal T_Y (1000–10000t) is characteristic of Sc and Rb, the elements little used nowadays by mankind, but with relatively high concentrations in the upper continental crust. A more detailed explanation of the technophility parameter is given in [Kasimov & Vlasov, 2012]. Currently, the most important from the technogenesis perspective are the elements with intensive production, i.e., C, Fe, S, N, Cl, Cu, Zn, Cr, Mo, and Sb.

Specific technophility (T_{YN}) represents change in AR production calculated per capita population (thousands tons per capita per year). This parameter can be used for comparison of the growth rate of the population and its demand for various chemical elements. In the mid 1960s, T_{YN} was equal to 6,4; it grew to 58,2 by the 1980s due to a sharp increase of the use of ultramicroelements that practically had not been previously used in the industry; then, it began to decline, reaching 47,2 in 2000 and 44,3 in 2010. This reduction in T_{YN} indicates that the world population in recent years is growing significantly faster than its demand for many chemical elements.

Regional intensity of technogenesis. Geochemical regional geography

Regional conditional technophility (T_{YR}) was incorporated in order to assess the technogenic contribution of 172 different world's countries to the total world's T_Y considering production of all chemical elements: $T_{YR} = \Sigma T_{Yi}$, where T_{Yi} is production of an *i*-chemical element in a country relative to AR (tons per year) (Fig. 2). This parameter represents an integral index of technogenesis at the regional level.

T_{YR} of the macroregions of the world varies from $3{,}6 \cdot 10^{11}$t in Central America to $1{,}4 \cdot 10^{13}$t in Asia (including Russia). Other countries occupy intermediate positions: Africa ($1{,}6 \cdot 10^{12}$t), Europe ($1{,}4 \cdot 10^{12}$t), North America ($1{,}3 \cdot 10^{12}$t), South America ($1{,}2 \cdot 10^{12}$t) and Australia and Oceania ($4{,}2 \cdot 10^{11}$t).

According to the values of T_{YR}, six groups of countries (with an order of magnitude step-difference between the individual groups) were isolated: *very high*, *high*, *intensive*, *medium*, *low*, and *very low* (Fig. 2).

Very high (> 10^{12}t). The leader of this group is Kyrgyzstan ($7{,}8 \cdot 10^{12}$t – Au, Hg, Mo, C, F, Sb, Na, Cl, and Ca); the group also includes China ($2{,}3 \cdot 10^{12}$t – practically all elements), South Africa, and Russia (each $1{,}1 \cdot 10^{12}$t– practically all elements).

High (10^{11}–10^{12}t). The group includes 21 "polyelemental" countries with a significant

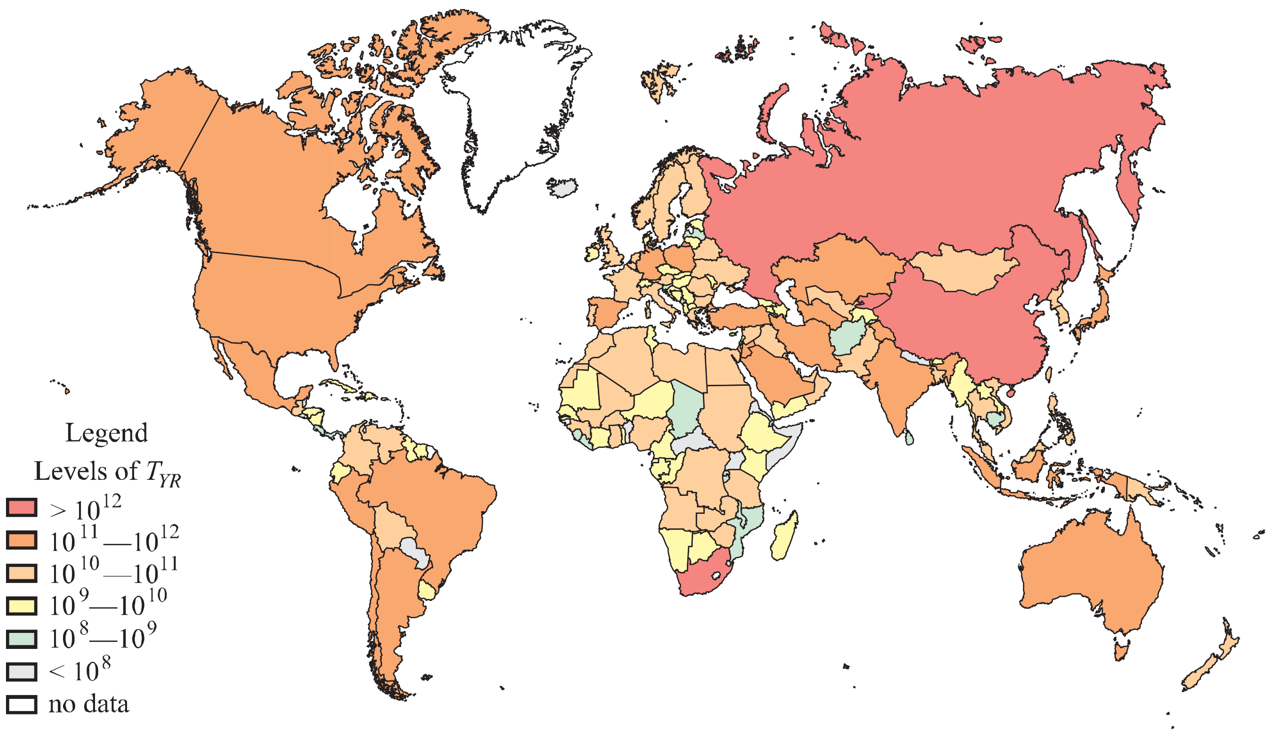


Fig. 2. Regional conditional technophility (T_{YR}) of different countries (tons per year)

production of a wide range of elements. In the descending order of T_{YR}, these countries are USA, Chile, Canada, Australia, Peru, Turkey, India, Mexico, Japan, Indonesia, Turkmenistan, Germany, Iran, Saudi Arabia, Kazakhstan, Poland, Brazil, Spain, Israel, Jordan, and Argentina. The main contribution to T_{YR} of these countries is provided by Na, Cl, Ca, Mg, S, N, P, B, Fe, Mn, heavy, non-ferrous, and precious metals. In addition, some of the countries have a large level of production of very toxic elements: As (Japan, Peru, Kazakhstan, Chile, and Iran), Hg (Peru, Mexico, Chile, and Argentina), and Sb (Canada, Australia, Japan, Peru, Kazakhstan, Mexico, and Turkey).

Intensive (10^{10}–10^{11}t). This group includes 55 "polyelemental" countries with a smaller list of produced elements. Many countries have high levels of C, S, Ca, Na, Cl, N, Si, Fe, Ag, Au, and non-ferrous metals production.

Medium (10^{9}–10^{10}t). This group has 53 countries with mining of either limited list of chemicals and high levels of their production, or a large number of elements with small production.

Low (10^{8}–10^{9}t). This group includes 20 countries that produce only some chemical elements: C, Ca, Na, Cl (almost all countries), Au (Mozambique, Rwanda, Burundi, Sierra Leone, Chad, Fiji, Costa Rica, Panama, and Liberia), Fe and Ti (Mozambique, Afghanistan, Sri Lanka, and Sierra Leone), Ta and Nb (Mozambique, Rwanda, and Burundi), S (Afghanistan, Latvia, and Malawi), Si (Mozambique, Sri Lanka, and Slovenia), Sn and W (Rwanda and Burundi), Ag (Fiji), U (Malawi), Mg (Latvia), P (Sri Lanka), Ba, Cr, and N (Afghanistan), and Be, Zr, and Hf (Mozambique).

Very low (< 10^{8}t). This group includes Uganda (Au, Be, C, Ca, Cl, Na, Nb, Sn, Ta, and W), Eritrea (Au, C, Ca, Cl, Na, Mg, and S), and the countries with mining of one to four chemical elements: Belize (Au, C, Ca, and Mg), Guadeloupe (C, Na, Cl, and Ca), Benin and Central African Republic (Au, C, and Ca), Paraguay (Ca, C, and S), Nepal (C, Ca, and Si), Iceland (Na, Cl, and Si), Barbados, El Salvador, and Haiti (C and Ca), Mauritius and Cape Verde (Na and Cl), Swaziland (C and V), Luxembourg (P), and Singapore, Puerto Rico, Netherlands Antilles, and Somalia (C).

In general, the expansion of the list of elements produced in a country is associated with the growth of its T_{YR}: the groups of intensive, high and very high T_{YR} include exclusively "polyelemental" countries, where a wide range of elements is produced, while the groups of low and very low T_{YR} include countries with mining of only isolated elements (C, Si, Na, Cl, Ca, Mg, N, P, S, Al, Fe, Mn, Ti, and heavy and precious metals).

Specific regional tehnophility and density of regional conditional technophility

For comparison between different countries by the intensity of technogenic or other parameters, it is feasible to use relative coefficients in addition to the absolute parameters. The relative coefficients should be calculated depending on the intended purpose in relation to population, area, or other physical, economic, or socio-geographical characteristics.

In order to estimate the per capita contribution to technogenesis of individual countries, the authors have calculated *specific regional tehnophility* (T_N), which is equal to the ratio T_Y/N, where T_Y is the volume of extracted AR in a country (t/yr) and N is the population of that country (persons) (Fig. 3). For the world as a whole, T_N is equal to 2,850 tons per capita per year. For the countries of the macroregions, T_N varies from 1,500 tons per capita per year in Africa to 15,400 tons per capita per year in Australia and Oceania. In North America, Asia, South America, Europe, and Central America, T_N is 3,800, 3,200, 3,100, 2,000, and 1,800 tons per capita per year, respectively.

Within the territories of relatively small countries, very rare elements can be produced (e.g., Nb and Ta in Rwanda, or Au

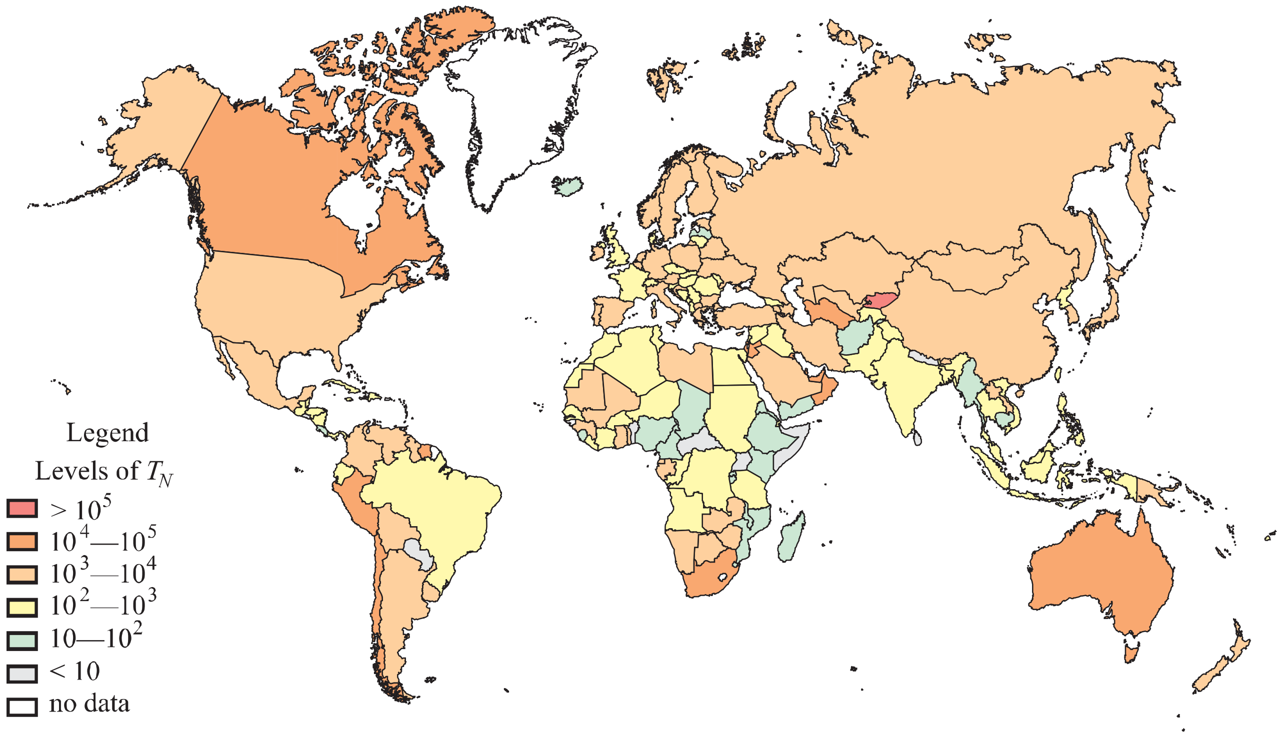


Fig. 3. Specific regional technophility (T_N) of different countries (tons per capita per year)

in Burundi, Togo, and Fiji). Therefore, their T_R values increase. In order to compare different countries with different levels of production of elements and area, *the density of regional conditional technophility of a country* (T_S) have been introduced; T_S equals to the ratio T_Y/S, where S is the area of a country (km^2) (Fig. 4). The world's level of T_S reaches 149 thousands t/km^2 per year. For the macroregions, T_S varies from 52,6 to 281 thousands t/km^2 per year in Australia-Oceania and Asia, respectively. T_S of Europe, Central America, South America, North

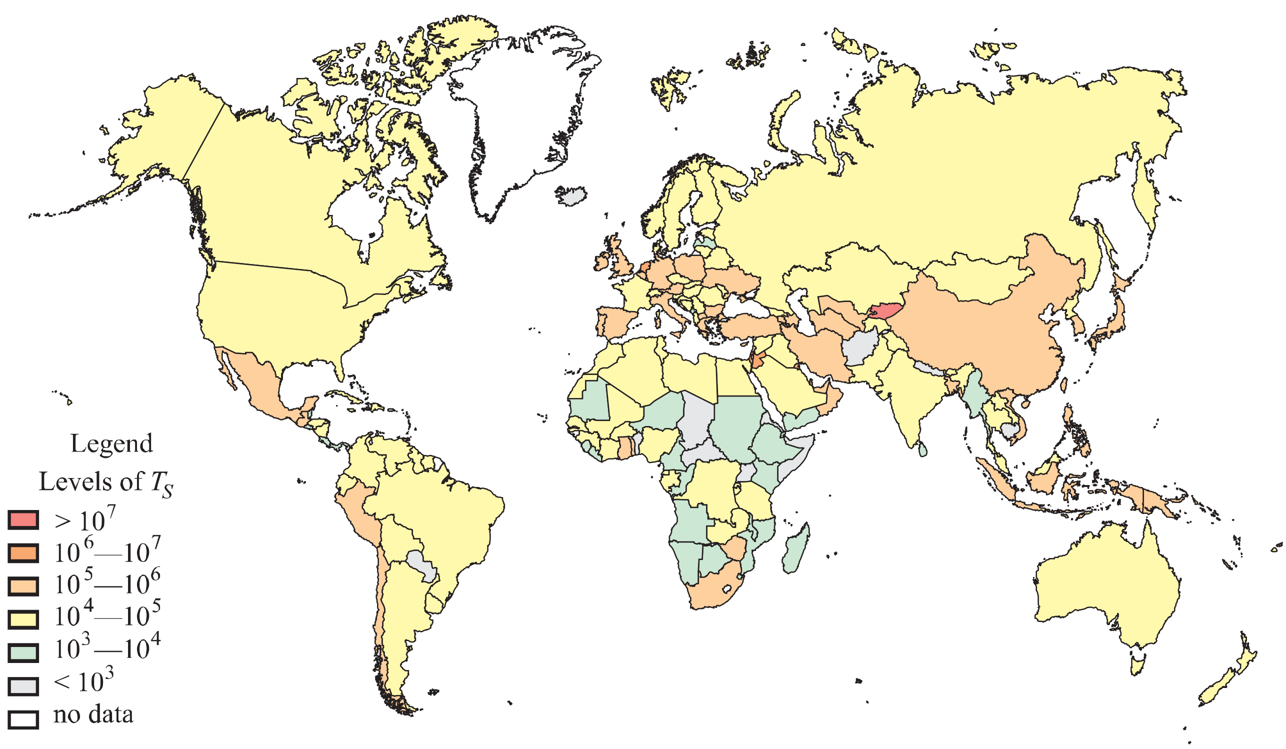


Fig. 4. Density of regional technophility (T_S) of different countries (tons per km^2 per year)

Table 1. The matrix array of the world's countries based on the intensity of technogenesis

Factor		Levels of TN (tons per capita per year)					
		Very low (<10)	Low (10–102)	Medium (102–103)	Intensive (103–104)	High (104–105)	Very high (>105)
Levels of TS (tons per km2 per year)	Very low (<103)	Cape Verde, Puerto Rico, Benin, Uganda, Nepal, CAR, Paraguay, Somalia, Haiti	Cambodia, Afghanistan, Eritrea, Chad, Iceland	–	–	–	–
	Low (103–104)	Sri Lanka, El Salvador, Mauritius	Burma, Ethiopia, Yemen, Netherlands Antilles, Cameroon, Costa Rica, Latvia, Sierra Leone, Malawi, Madagascar, Kenya, Swaziland, Mozambique	Montenegro, Angola, Panama, Djibouti, Sudan (with S. Sudan), Congo-Brazzaville, Liberia, Niger, Belize	Namibia, Mauritania, Botswana	–	–
	Medium (104–105)	–	Singapore, Rwanda, Burundi, Luxembourg, Nigeria	Denmark, Thailand, Czech Rep., D.P.R. Korea, Jamaica, Slovakia, France, India, Egypt, Malaysia, Albania, Romania, Hungary, Serbia, Georgia, Switzerland, Syria, Dominican Rep., Pakistan, Cuba, Tajikistan, Bosnia & Herzegovina, Guadeloupe, Fiji, Morocco, Moldova, Iraq, Burkina Faso, Honduras, East Timor, Tanzania, Tunisia, Nicaragua, Lithuania, Brazil, Slovenia, Senegal, Cote d'Ivoire, Algeria, Ecuador, Congo-Kinshasa	USA, Croatia, Norway, Equatorial Guinea, Belarus, Saudi Arabia, Kazakhstan, Russia, Sweden, Bolivia, Venezuela, Finland, Guinea, Estonia, New Zealand, Colombia, Zambia, Laos, Argentina, Uruguay, Bhutan Guyana, Mali, Libya, Gabon, Mongolia	Australia, Suriname, Canada	–
	Intensive (105–106)	–	–	Malta, Taiwan, Lebanon, Martinique, UK, Barbados, Bangladesh, Philippines, Indonesia, Vietnam, Guatemala	Belgium, R. Korea, Japan, Germany, Gambia, Turkey, Poland, Armenia, Austria, Brunei, Bulgaria, China, Spain, Ghana, Italy, Uzbekistan, Macedonia, Togo, Cyprus, Ireland, Greece, Mexico, New Caledonia, Portugal, Bahamas, Zimbabwe, Azerbaijan, Iran, Papua New Guinea, Ukraine	South Africa, UAE, Chile, Turkmenistan, Peru, Oman	–
	High (106–107)	–	–	–	Netherlands	Aruba, Qatar, Israel, Kuwait, Jordan	–
	Very high (>107)	–	–	–	Bahrain	Trinidad & Tobago	Kyrgyzstan

America, and Africa is 196, 133, 69,4, 66,9, 53,7 thousands t/km^2, respectively.

According to the values of T_N and T_S, the countries were combined into six groups (with an order of magnitude step-difference between the individual groups): *very high*, *high*, *intensive*, *medium*, *low*, and *very low* (Fig. 3 and 4). The *very high* ranking was assigned for the T_N values of higher than 10^5 tons per capita per year and for the T_S values higher than 10^7 t/km^2 per year. Eighteen groups of countries were isolated considering concurrently T_N and T_S (Table 1). Table 1 is a matrix array of T_N and T_S values that should be considered in combination.

The countries whose values of T_N and T_S depend on the intensity of production of chemical elements are located on the main diagonal of the matrix. Thus, low and very low T_N and T_S values are typical of small and medium-sized, in terms of population and area, countries where only some elements are produced (C, Ca, Na, Cl, S, Au, Si, Fe, Ti, and non-ferrous metals). Further increase of T_N and T_S occurs due to expansion of the list of produced elements and the intensity of their production.

Very high or *high* T_N and T_S are characteristic of relatively small, in terms of population and area, countries with intensive and medium level of production of chemical elements (Aruba, Israel, Kuwait, Jordan, Qatar, and Trinidad and Tobago), as well as of Kyrgyzstan that stands out as a country with the enormous T_{YR} reaching the level of T_{YR} for the major resource extraction countries, i.e., Russia, China, and South Africa.

The location of the countries in the cells next to the main diagonal may occur in the following cases: if production of chemical elements is comparable with the intensity of technogenesis in the countries of the main diagonal, the countries with a greater or smaller populations are located in the matrix to the left or to the right of the main diagonal, respectively, while countries with greater or smaller areas are located above or below the main diagonal. However, the values of both T_N and T_S for different countries in the cells adjacent to the main diagonal do not differ significantly. For example, for Russia, USA, and Kazakhstan with intensive chemical elements production, the level of T_S is *medium* because of the giant territories. On the other hand, The Netherlands, by the reason of small territory, is set into the group with *high* T_S. That is why the authors suggest considering such countries in the *intensive* T_N–T_S group.

Countries that are not in the adjacent to the main diagonal cells have "*very high*" T_S due to a small area (Bahrain), *low* levels of T_N, or *high* levels of T_S due to the low density of the population of about 3 persons per km^2 (Australia, Canada, Suriname, Namibia, Mauritania, and Botswana).

Analysis of Table 1 and Figs. 2–4 allows identifying countries with significant absolute elements production and with high levels of relative parameters of technogenesis, i.e., with *intensive*, *high*, and *very high* T_{YR}, T_N, and T_S: Kyrgyzstan, China, South Africa, Chile, Peru, Turkey, Mexico, Japan, Turkmenistan, Germany, Iran, Poland, Spain, Israel, Jordan, Uzbekistan, R. Korea, Trinidad and Tobago, Ukraine, Qatar, Italy, UAE, Ghana, Netherlands, Papua New Guinea, Zimbabwe, Kuwait, Oman, Bulgaria, Austria, Belgium, Greece, Bahrain, and Portugal. The leaders in the production of various minerals with the giant absolute levels of technogenesis have low relative regional parameters: Russia, USA, Canada, Australia, Saudi Arabia, Kazakhstan, Argentina, Bolivia, Venezuela, Colombia, Zambia, Mali, Libya, Mongolia, Sudan (with South Sudan) – because of large territories; Indonesia, Vietnam, Philippines, Bangladesh, Nigeria – because of significant population; while India, Brazil, France, Egypt, Thailand, Pakistan, Algeria, Tanzania, Congo (Kinshasa), Malaysia, Morocco (with Western Sahara) – because of both high spatial and demographic dimensions.

Thus, the proposed integral parameters allow comparing the relative intensity of technogenesis of the countries with very different demographic and spatial dimensions. They account for a wide range of chemical elements and are effective in identification, for example, of small countries with high levels of elements production, or on the contrary, of large countries with low levels.

CONCLUSION

The "geochemical" approach provides for comparison of certain aspects of technogenesis intensity in different countries and represents analysis of various factors and indices, among which the most useful are tehnophility and its derivatives.

For concurrent comparison of the intensity of production of chemical elements, the authors have introduced the concept of elemental equivalent, i.e., "abstract rock" whose average chemical composition coincides with the average chemical composition of the upper continental crust. The authors have also introduced new parameters. "*Conditional technophility*" (T_Y) represents the number of tons of AR per year, necessary for production of the current level of an element. Because of the high level of contrast and temporal variability, T_Y is a useful indicator of the level of technogenesis in different countries. Calculation of the sum of T_Y for different chemical elements allows assessing their integral involvement in technogenesis. The highest T_Y values are associated with C, S, N, Ra, and Au. T_Y of many micro- and ultramicroelements is of the order of $n \cdot 10^{11}$t. T_Y is minimal for Sc and Rb that, though they have relatively high concentrations in the upper continental crust, are little used by mankind so far.

"*Specific technophility*" (T_{YN}) reflects the volume of AR per the world's capita. Analysis of the changes from the 1960s to 2010 indicates that the Earth's population is growing much faster than its demand for many chemical elements.

In order to integrally assess the regional aspects of technogenesis, the authors have also used: T_{YR}, T_N, and T_S – "regional conditional technophility," "specific regional technophility," and "density of regional conditional technophiliy," respectively. These parameters indicate the intensity of involvement of a range of chemical elements in technogenesis, depending on the population and physical size of a country. The highest T_{YR} is associated with Asia and Europe, while the lowest – with Central America and Australia-Oceania.

Considering T_N and T_S concurrently, it was possible to isolate 18 groups of countries that differ in the lists of produced chemical elements and in the intensity of the primary mobilization of the elements in technogenesis. *Low* and *very low* T_N and T_S values are typical of small and medium-sized, in terms of population and area, countries where only individual elements are produced; *high* and *very high* T_N and T_S values – of small countries with intensive and medium levels of production of chemical elements (Aruba, Trinidad and Tobago, Kuwait, Qatar, Israel, and Jordan), as well as of Kyrgyzstan with its enormous volume of elements production.

The authors have isolated the countries with high levels of the absolute and relative parameters of technogenesis: in Asia – Kyrgyzstan, China, Japan, Turkmenistan, Iran, Israel, Jordan, Uzbekistan, R. Korea, Qatar, UAE, Papua New Guinea, Kuwait, Oman, and Bahrain; in Europe – Turkey, Germany, Poland, Spain, Ukraine, Italy, Netherlands, Bulgaria, Austria, Belgium, Greece, and Portugal; in Africa – South Africa, Ghana, Zimbabwe; and in South America – Chile, Peru, Mexico, and Trinidad and Tobago.

The relative indicators of technogenesis of the leaders in extraction of natural resources are below these values in other countries due to the large territories (Russia, USA, Canada, Australia, Saudi Arabia, Kazakhstan, Argentina, Bolivia, Venezuela, Colombia, Zambia, Mali, Libya, Mongolia, and Sudan), to the large population (Indonesia, Vietnam, the Philippines, Bangladesh, Nigeria), or to both high spatial and demographic dimensions (India, Brazil, France, Egypt, Thailand, Pakistan, Algeria, Tanzania, Congo (Kinshasa), Malaysia, and Morocco). ■

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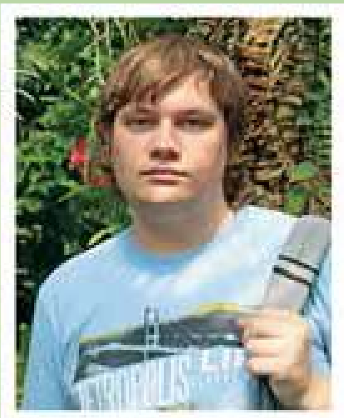

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