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Mapping Chemical Earth Program: Progress and challenge

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ABSTRACT

There is a critical need to establish a global geochemical observation network to provide data for monitoring the chemical changes of the Earths near-surface environment. The International Centre on Global-scale Geochemistry, under auspices of UNESCO and Government of China, has initiated an International Scientific Cooperation Project called *Mapping Chemical Earth*. The project focuses on the establishment of Global Geochemical Observatory Network for documenting baselines and changes of nearly all natural chemical elements in the Earths surface and creating a digital Chemical Earth platform allowing anyone to access vast amounts of geochemical data through the Internet. A total area of about 37 million km^2, nearly accounting for 27% of the global land, has been covered by global-/continental-scale sampling. Comparing the data of China, the US, Europe and Australia, the percentage of sites with toxic metals exceeding the risk limits of soil pollution according to “Environmental Quality Standard for Soil of China (GB 15618-1995)” to the total sample sites is 30.9%, 17.1%, 23.5% and 10.9% in Europe, China, USA, and Australia respectively. Comparing the China datasets of 15 years interval sampling between 1994, 1995 and in 2008–2012, toxic metals of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn, particularly Cd at top soils significantly increase from 1990s to 2010s. The proportion of top soil samples exceeding the China Standard risk limit of 0.2 mg/kg Cd increases from 12.2% to 24.9%. The facts show that chemical changes of toxic metals induced by human activities can be well observed using catchment sediment sampling.

1. Introduction

Ninety-two chemical elements naturally occur on the Earth. Everything in and on the Earth – mineral, animal and vegetable – is made from one, or generally some combination of, the chemical elements listed in the periodic table. Global-scale data are critically needed for better understanding the Earth, for solving major issues on global resources and the environment, and for harmony between man and nature. In light of the importance of global data, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Medium-Term Strategy declares “building on its experience in leading intergovernmental and international science programs and bodies and on their global observation capacities, UNESCO will contribute to shaping the research agenda of global and regional scientific cooperation” (https://unesdoc.unesco.org/ark:/48223/pf0000227860). However, the global-scale geochemical data were unavailable until recently although there are well-established global observation characterized by physics using satellite and remote sensing technology such as DigitalGlobe™ (https://www.digitalglobe.com/), Google Earth (www.google.com), and BaiduMap (https://map.baidu.com). The International Centre on Global-scale Geochemistry (ICGG), operating under the auspices of UNESCO and the government of China, initiated an International Scientific Cooperation Project called *Mapping Chemical Earth* in 2016, which will establish Global Geochemical Observation Network to provide global-scale geochemical data for natural resources and environmental management.

Before 2015, The Environmental Geochemical Monitoring Networks (EGMON project) between 1994 and 1996 in China (Xie and Cheng, 1997), The Geochemical Baseline Mapping Programme of the Forum of European Geological Surveys (FOREGS, now EuroGeoSurveys) between 1997 and 2006 (Plant et al., 1996, 1997; Salminen et al., 1998; Salminen et al., 2005), National Geochemical Survey of Australia

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(NGSA) (Johnson, 2006; Caritat et al., 2008; Caritat, 2009; Caritat and Cooper, 2011; Caritat de et al., 2018) between 2006 and 2011, the North American Soil Geochemical Landscapes Project (NASGL) with work in the conterminous U.S. between 2007 and 2013 (Smith, 2009; Smith et al., 2009, 2012a, 2012b, 2013, 2019; Friske et al., 2013), China Geochemical Baselines (CGB) Project between 2008 and 2014 (Wang and the Sampling Team, 2015; Wang et al., 2015), Geochemical Mapping of Agricultural Soils (GEMAS) project in Europe (Reimann et al., 2012a, 2012b, 2014, 2018) have covered a total area of about 32 million km^2, nearly accounting for 22% of the global land area (Fig. 4 green color dots).

The primary purpose of geochemistry is to determine quantitatively the composition of the earth and its parts, and to discover the laws which control the distribution of the individual elements (Goldschmidt, 1937). How do we know the distribution of the individual elements on the Earth in time and space? Geochemical mapping is a principal technique to illustrate the spatial distribution of elements and their compounds by systematic sampling of minerals, rocks, soils, drainage sediments and waters. The goal of "*Mapping Chemical Earth*" is to provide data and maps to present the spatial variation and distribution of chemical elements in the periodic table in the Earths near-surface environment. This will be accomplished by systematic sampling, at the global scale, of selected sample media conducted periodically at designated time intervals. Such data will provide a current baseline for the analyzed chemical elements and will also allow the recognition of changes in the geochemistry of Earths near-surface environment over time caused by either human activities or natural processes. The purpose of this paper is to give a brief introduction about the progress and challenges of the program.

2. Research focus and planning

2.1. Research focus

The project will focus on the following: 1) establishing a Global Geochemical Baselines Network for documenting baselines of nearly-all natural chemical elements in the Earths near-surface environment, 2) establishing the China Geochemical Observation Network, which will be based on the China Geochemical Baselines (CGB) Network completed between 2008 and 2014, for temporal sampling to recognize and quantify potential environmental changes of chemical elements, including potentially toxic elements, radioactive elements and natural carbon, 3) providing baseline datasets of around 50 ore-related elements for mineral resource assessment, 4) determining possible geochemical response to major historic geological events, such as extinction episodes and ancient climate change, 5) compiling the Silk Road Geochemical Atlas from Asia to Europe, 6) creating a digital Chemical Earth platform allowing anyone to access vast amounts of geochemical data and maps through the Internet.

2.2. Planning

The project will be a long-term endeavor. The first phase will last 6 years from 20162021. The project was initiated during the opening ceremonies of the ICGG. A draft proposal was distributed to the worldwide participants in the ceremonies and revised after receiving comments from these participants. The final proposal, including "Initiative For International Scientific Cooperation Project of Mapping Chemical Earth" and "International Scientific Cooperation Project on Mapping Chemical Earth" were drafted in 2016 and "UNESCO-ICGG Protocol of Global Geochemical Baselines" which particularly focuses on large basin catchment sediment sampling was completed and agreed by the ICGP Scientific committee in 2018. In the first phase for 6 years from 2016 to 2021, it is planned to 1) continue to establish global geochemical baselines through analysis of approximately 5000 samples from 2500 sites based on each grid cell of 80 km by 80 km by the ICGG cooperation Global Geochemical Baselines projects and 5000 samples selected floodplain or overbank sediments or alluvial soils from 2500 sites based on each grid cell of 80 km by 80 km or 160 km by 160 km of the completed continental-scale geochemical baselines projects (FOREGS, Salminen et al., 1998; GEMAS, Reimann et al., 2012a, 2012b; NGSA, Caritat et al., 2008; NASGL, Smith, 2009. additional analyses of chemical elements which were not determined if the samples are available) covering approximately a third (33%) of the whole globe, 2) conduct a pilot study on the establishment of Geochemical Observation Network through the second-round sampling based on the China Geochemical Baselines networks (CGB project, Wang and the Sampling Team, 2015) 3) produce geochemical Atlas in cooperation with the countries along "the Silk Road" covering from China-Mongolia-Laos-Cambodia-Pakistan-Uzbekistan-Iran-Turkey-Southern Europe based on available data and newly obtained data, 4) create a big data platform for "*Chemical Earth*" based on the internet.

2.3. Cooperation with other countries

All countries are welcome to participate in the project. Participating countries must sign Memorandums of Understanding between the participating governments or governmental Geological Surveys and the China government through the China Geological Survey. International scientific organizations and scientists are welcome to participate in the program.

Participating countries will be divided into three categories according to their capabilities. Category 1: The countries have capability to conduct both sampling and laboratory analysis. The ICGG will conduct chemical analysis for the elements that are not analyzed in their continental projects. The data will be into the global data platform after evaluating the data quality according to the preliminary studies and criteria (Reimann et al., 2012a, 2012b; Liu et al., 2015; Wang et al., 2020) and the new criteria or protocol which will be proposed by the ICGG and agreed by the IUGS commission on Global Geochemical Baselines or the ICGG scientific committee. Category 2: The countries have capability to conduct the sampling work after training, but the laboratories are not technologically qualified or lack of financial support to conduct chemical analysis. China will provide chemical analysis of 76 elements. Category 3: The countries do not have capability to conduct the sampling and analysis work, China will give assistance for both sampling and analysis. Any government or organization wanting to participate in the project must agree to make the data for their country available to the public.

3. Global sampling progress

The issues of global change, such as climate change caused by carbon emissions, and changes of potentially toxic elements induced by human activities, are the focus of public concern in todays society. A major problem about global change is the lack of global baseline data that can be used to quantify potential changes. Just as Zoback (2001) said, "How do we recognize and understand changes in natural systems if we don't understand the range of baseline levels." Since 1988, there has been significant progress by applied geochemists in implementing the recommendations of Darnley (1995) regarding establishing a global geochemical database (Plant et al., 1996; Xie and Cheng, 1997; Salminen, 2005; Caritat et al., 2008; Smith, 2009; Reimann et al., 2012a, 2012b; Wang and the Sampling Team, 2015).

Darnley (1995) recommended global-scale sampling of multiple sample media (stream sediment, soil, floodplain sediment, overbank sediments, humus, stream water) based on a global geochemical reference network (GRN) consisting of a grid of about 5,000 cells of approximately 160 km × 160 km covering the entire land surface of the Earth. Generally, each GRN grid cell is divided into 4 quadrants (80 km × 80 km) or 16 quadrants (40 km × 40 km) for small countries (Fig. 3), totaling about 18,000 sub-grid cells worldwide. The *Mapping*

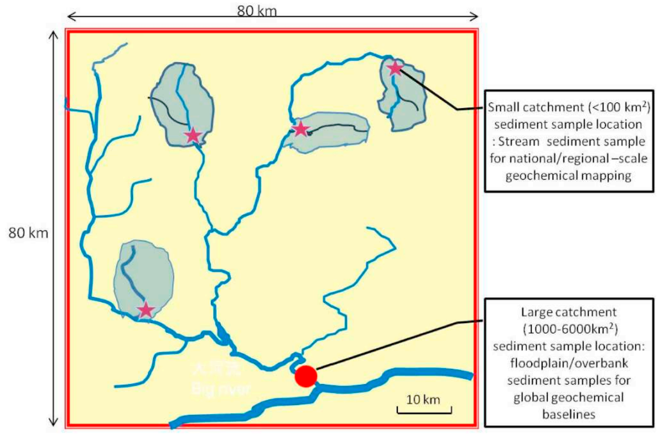

Fig. 1. Sample location design for large and small catchment sediment sampling.

Chemical Earth Program proposes to collect catchment sediment samples at the outlet of the largest drainage basin of each sub-grid cell to provide a global-scale geochemical database.

At each sampling site, two depth-based samples will be collected. The top sample is collected from 0 to 25 cm, representing the current baseline, which included input from human activities as well as natural processes; the bottom sample is collected a depth of 100–150 (generally 100–125 cm) cm, which will more closely represent the natural background before industrialization. There are 18,000 sites and 36,000 samples totally. Coupled with 5% of duplicate samples, there are about 40,000 samples totally. In this plan, 76 chemical elements of Ag, As, Au, B, Ba, Be, Bi, Br, C, Cd, Cl, Co, Cr, Cs, Cu, F, Ga, Ge, Hf, Hg, I, In, Li, Mn, Mo, N, Nb, Ni, P, Pb, Pd, Pt, Rb, S, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Ti, Tl, U, V, W, Zn, Zr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Re, Ir, Os, Rh, Ru, SiO_2, Al_2O_3, TFe_2O_3, MgO, CaO, Na_2O, K_2O, and CO_2, Organic C, and pH will be analyzed (Fig. 1).

The ICGG have cooperated with Laos, Cambodia, Mongolia, Colombia, Turkey, Iran, Russia, Uzbekistan, Pakistan, Papua New Guinea, and Indonesia to take a total of 1144 samples covering an area of about 4,900,000 km^2 (Fig. 2, Blue color dots) from 2016 to 2018. The total coverage of the global geochemical baseline map in including all continental projects (Plant et al., 1996; Xie and Cheng, 1997; Salminen, 2005; Caritat et al., 2008; Smith, 2009; Reimann et al., 2012a, 2012b; Wang and the Sampling Team, 2015) has reached 27% of the land area of the Earth till 2018 (Fig. 3).

4. Preliminary results

4.1. Global assessment of toxic metals

The geochemical baseline data of 10 toxic metals (Cd, Hg, As, Sb, Pb, Zn, Cr, Co, Ni and V) from FOREGS (soil sample), NGSA (catchment sediments), NASGL (soil samples) and CGB (catchment sediments/alluvial soils) were taken as an example to evaluate the soil environmental risk status. The risk limits or guidelines for soil protection has introduced by many countries and international organizations such as China, US EPA, Europe, UNEP, WHO and so on. Most of the standards only give a safe limit for each toxic metal in soils. China standard gives 3 grade risk limits (slight, moderate and heavy pollution), thus the authors will evaluate the risk status according to "Environmental Quality Standard for Soil of China (GB 15618-1995)" (Table 1) in order to have a good understanding of the changes for different concentrations. Comparing the data of China, the US, Europe and Australia, it is concluded that the percentage of sites with toxic metal concentrations exceeding the risk limits of slight pollution of 8 toxic metals to the total number of sample sites is 30.9%, 17.1%, 23.5% and 10.9% in Europe, China, USA and Australia respectively, exceeding the limits of heavy pollution of the 8 toxic metals is 10.9%, 4.1%, 2.6% and 1.8% in Europe, China, the USA and Australia respectively (Fig. 4). Slight pollution from toxic metals in soils is most prevalent in Europe, followed by the USA. Heavy pollution of soils by toxic metals is most prevalent in Europe, followed by China. Australia has the fewest occurrences of samples that exceed the stated limits. These observations may be due, as least in part, to the long industrial history of Europe and the rapid development and industrialization of the past 30 years in China.

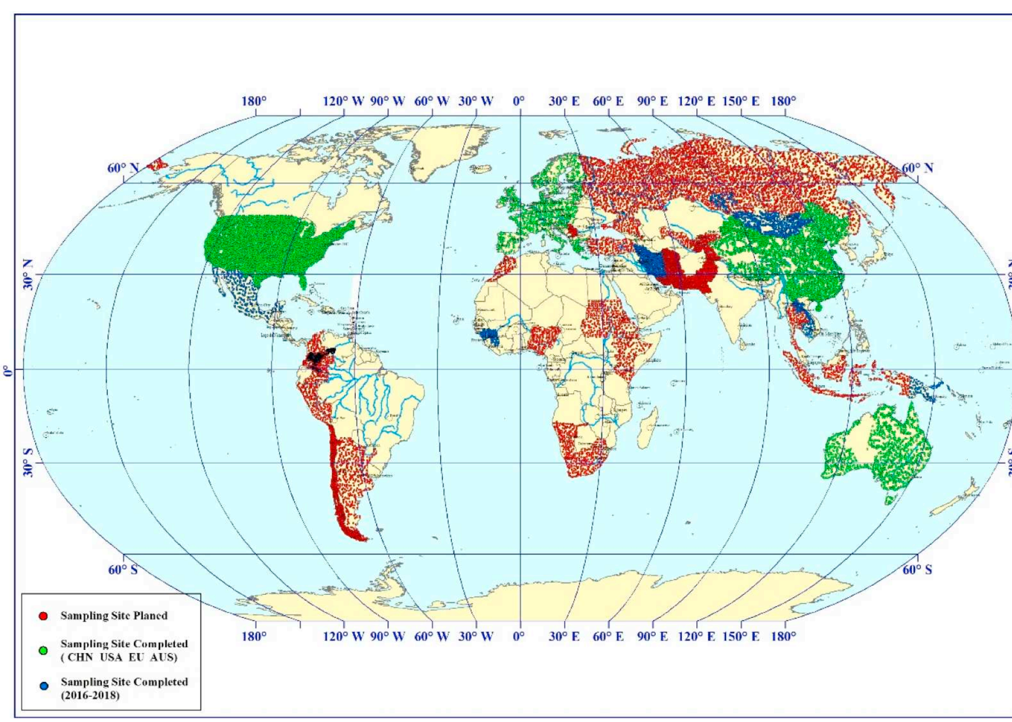

Fig. 2. Sampling locations of global geochemical baselines.

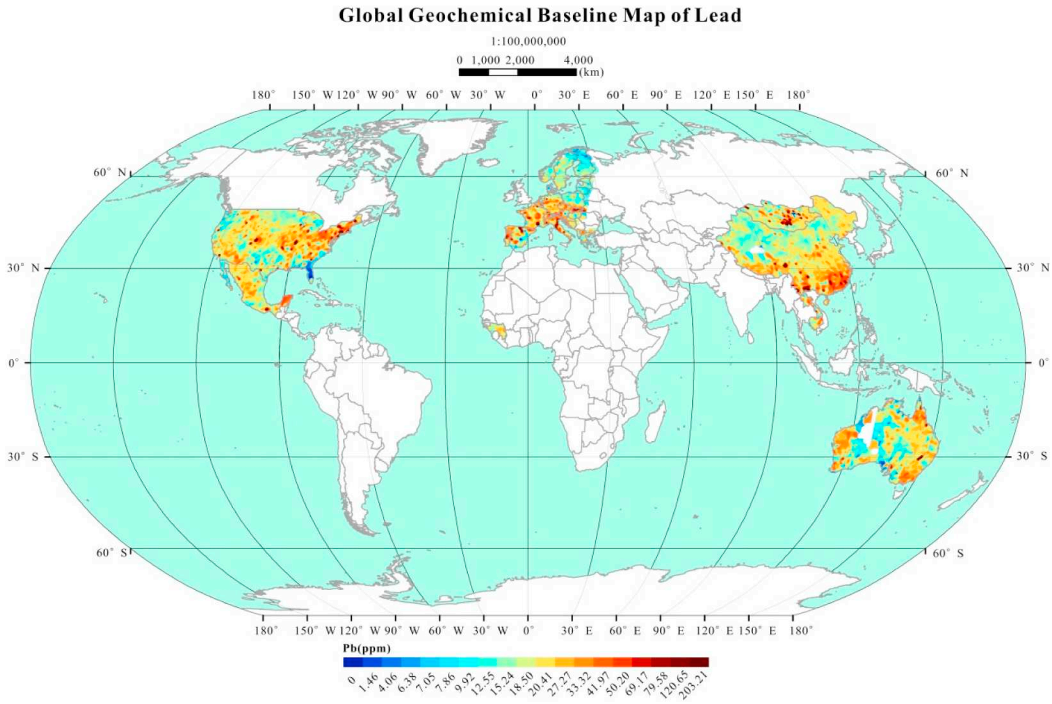

Fig. 3. Global map of lead covering 27% of Earth's land surface.

Table 1
Risk limit concentration standards (mg/kg) for toxic metal pollution of soils in China (GB 15618-1995).

	1st grade (slight pollution)	2nd grade (moderate pollution)	3rd grade (heavy pollution)
As (mg/kg)	15	25	30
Cd (mg/kg)	0.2	0.3	1
Cr (mg/kg)	90	300	400
Cu (mg/kg)	35	100	400
Hg (mg/kg)	0.15	0.5	1.5
Ni (mg/kg)	40	50	200
Pb (mg/kg)	35	300	500
Zn (mg/kg)	100	250	500

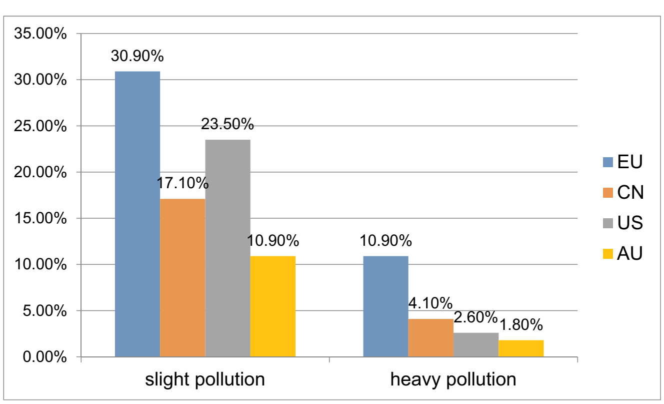

Fig. 4. Percentage of top samples with toxic metal values exceeding risk limits of soil environment quality standards in China (GB 15618-1995).

4.2. Temporal changes from the China Geochemical Observation Networks

The database and accompanying element distribution maps represent a geochemical baseline against which can be quantified future human-induced or natural changes to the chemistry of the Earth (Darnley, 1995; Smith et al., 2012b). What kind of samples can quantify environmental changes? Catchment sediments (overbank and floodplain sediments, alluvial regolith/soils) may provide useful data relevant to temporal changes, including anthropogenic effects (Darnley, 1995). Alluvial Regolith/Catchment sediments are better than other media to quantify or recognize natural spatial distribution and environmental changes of elements. Contamination in catchment sediments can build relatively quickly. Pollution comes from diffuse sources such as natural weathering, industries, residents, pesticides and fertilizers. Rain falling on the land picks up natural and anthropogenic elements and moves them by both physical and chemical transportation into watercourses. When these watercourses flood, these elements may be deposited in the overbank, floodplain, basin and delta sediments (Fig. 5). By sampling these sediments at increasing depth, a temporal history of elements being transported in the watercourse may be

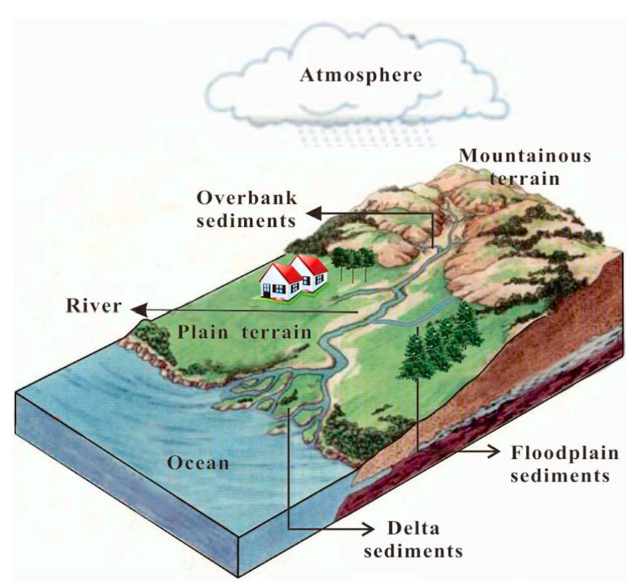

Fig. 5. Chemical elements and pollutants may be transported into watercourses and deposited in overbank, floodplain, basin and delta sediments.

determined. It is also possible to collect samples at a given site at appropriate intervals in order to determine possible geochemical changes. In China, interval between sampling will be every 10 to 15 years.

The authors have taken the datasets and maps obtained by the Environmental Geochemical Monitoring Networks project (EGMON) sampling in 1994–1995 (Xie and Cheng, 1997) and China Geochemical Baselines project (CGB) in 2008–2012 (Wang et al., 2015) as an example to quantify the environmental changes. The sample media are the consistent or similar both in the two projects. Floodplain sediments were taken in plains of eastern China, overbank sediments in mountainous terrains of western China. But the difference is that no samples taken by the EGMON project because floodplain sediments are no available in desert terrains, whereas samples taken at the lowest place or seasonal lake by the CGB project in desert terrains. The samples are also called alluvial soils. A total of 845 top-soil sample sites covered about 70% land surface of the whole China except desert terrains, corresponding to a sampling density of about 1 sample/15000 km^2. A total of 3284 top-soil sample sites covered the whole of China (9.6 million km^2), corresponding to a density of approximately one sample site per 3000 km^2.

The toxic metals As, Cd, Cr, Cu, Hg, Ni, Pb and Zn were selected for study. The results show that 1) The medians for each element are consistent. The median ratios of CGB to EGMON for the 8 toxic metals ranges from 0.9–1.20. Median of Cadmium slightly increase from 0.12 mg/kg to 0.14 mg/kg; 2) The contents of Cd in top soils from 0 to 25 cm significantly increased, for example, average values of Cd from0.15 mg/kg (EGMON) to 0.26 mg/kg (CGB) mg/kg, and geometric means from 0.11 mg/kg to 0.15 mg/kg, the CGB are 1.7 (athrimetric) and 1.4 (geometric) times that determined by EGMON respectively. 3) The number of sites with high values over the accumulative 85% relative to the total number of sample sites significantly increase, for example Cd from 10.9% to 22.7%, Hg from 24.4% to 30.7%, As from 5.8% to 10.7%, Cu 4.3% to 11.8%, Ni 3.9% to 7.1%, Zn 5.8% to 8.3%. The facts show that chemical changes of toxic metals induced by human activities can be well observed using catchment sediment sampling.

The spatial distribution patterns of Cadmium in the collected soil samples are mainly governed by geology (Reimann et al., 2018). Cadmium in top soils is significantly impacted by human activities though. When comparing the statistical parameters of CGB and EGMON top soil samples, it is found that Cd contents and distribution areas significantly increase from 1990s to 2010s. Table 2 shows the statistical parameters of Cd concentrations for EGMON and CGB projects. For EGMON project, the median Cd in top samples is 0.12 mg/kg and in deep samples 0.12%, with a range varying from 0.02 mg/kg to 3.06 mg/kg in top samples and 0.02 mg/kg to 0.44 mg/kg in deep sample. For CGB project, the median Cd in top samples is 0.14 mg/kg and in deep samples 0.11 mg/kg, with a range varying from 0.02 mg/kg to 45.98 mg/kg in top samples and 0.02 mg/kg to 21.2 mg/kg in deep samples. The results show that there is no difference for low abundance (P25) and median abundance (P50) between the two projects, but significant difference for mean concentrations in top samples from 0.15 mg/kg in the EGMON to 0.26 mg/kg in the CGB.

Table 3 lists the proportion of sample sites relative to total sampling locations that exceed the Cd risk limit values of 0.2 mg/kg–0.3 mg/kg for the 1st grade pollution soil (slight pollution), 0.3 mg/kg–1.0 mg/kg for the 2nd grade pollution soil (moderate pollution), and > 1.0 mg/kg for the 3rd grade pollution soil (heavy pollution) set by the National Soil Environmental Standards for Heavy Toxic Metals of the People's Republic of China (GB 15618-1995). Therefore, the proportion of top soil samples exceeding the risk limit of 0.2 mg/kg (slight pollution) Cd increase from 12.2% to 24.9%, exceeding risk limit 0.3 mg/kg (moderate pollution) from 4.3% to 12.3%, exceeding risk limit 1.0 mg/kg (heavy pollution) from 0.4% to 2.1% of total sample sites from 1990s to 2010s, respectively. The remarkable changes mainly occur in the southern part of China where base metal mineral deposits are mined, at lower reaches of the Pearl River of southern China where the largest industrial metropolis region is located in China, and at lower reaches of Yangtze river where is the highest density population region.

4.3. Data management based on the “Chemical Earth” platform

Chemical Earth software was developed based on Windows (Nie et al., 2012). Users can use it for retrieval, query and statistics based on spatial geographic coordinate multiple levels (national, regional and local), with visual interface and convenient operation mode, users can determine geochemical characteristics of different geological units or locations. Fig. 6 shows the windows of the “Chemical Earth” platform. Forty elements and 12 maps have uploaded onto the Chemical Earth (www.globalgeochemistry.com).

5. Challenge

5.1. Long way to go for global coverage

Significant progress of Global Geochemical Baselines Project conducted by the IUGS Commission on Global Geochemical Baselines and by the UNESCO ICGG has made since the International Geochemical Mapping Project (IGCP 259, 1988–1992) and Global Geochemical Baselines Project (IGCP 360, 1993–1997). According to the project, under the coordination of the IUGS Commission on Global Geochemical Baselines and the support of participating country governments, China, USA, Australia, EU, Mongolia, Colombia, Laos, Cambodia have completed the project, which covered a total area of about 37 million km^2, nearly accounting for 27% of the global land till 2018 by different countries used different sampling and analytical methods. The progress has laid a solid foundation for establishing global geochemical reference networks and monitoring global changes though combining these different data sets to generate a global-scale geochemical would be a challenge. We still have a long way to go for attracting more countries to participate in the project to cover the total land surface of the Earth though 69 countries have expressed interest in participating in the project, and 29 countries have signed an agreement with China until 2018.

5.2. Methodologies and criteria needed to be standardized

5.2.1. Sampling

The ICGG has prepared a protocol based on large catchment sediment sampling. The sampling methods were designed and widely used in plains, mountains, desert terrains, but the methods are not studied in glacial terrains.

Table 2
Statistical parameters for Cd from EGMON and CGB project.

Project	Sample	Analytical method	Detection limit	Min	Arithmetric mean	Geometric mean	Median	25%	75%	Max
EGMON	Topsoil	4 Acid-ICP-MS	0.02 mg/kg	0.02	0.15	0.11	0.12	0.09	0.16	3.06
1994–1996	Deepsoil	4 Acid-ICP-MS	0.02 mg/kg	0.03	0.13	0.11	0.12	0.09	0.16	0.44
CGB	Topsoil	4 Acid-ICP-MS	0.02 mg/kg	0.02	0.26	0.15	0.14	0.1	0.2	45.98
2008–2012	Deepsoil	4 Acid-ICP-MS	0.02 mg/kg	0.02	0.17	0.12	0.11	0.08	0.16	21.2

Table 3
Proportion of samples relative to total sampling locations that exceed the Cd risk limit values.

Years	Sample	Total	Clean background < 0.2 mg/kg		Slight pollution 1st grade 0.2–0.3 mg/kg		Moderate pollution 2nd grade 0.3–1.0 mg/kg		Heavy pollution 3rd grade > 1.0 mg/kg	
EGMON 1994–1996	Top	845	742	87.8%	103	12.2%	36	4.3%	3	0.4%
	Deep	468	405	86.5%	63	13.5%	15	3.2%	0	0.0%
CGB 2008–2014	Top	3284	2468	75.2%	816	24.9%	405	12.3%	69	2.1%
	Deep	2943	2499	84.9%	444	15.1%	210	7.1%	30	1.0%

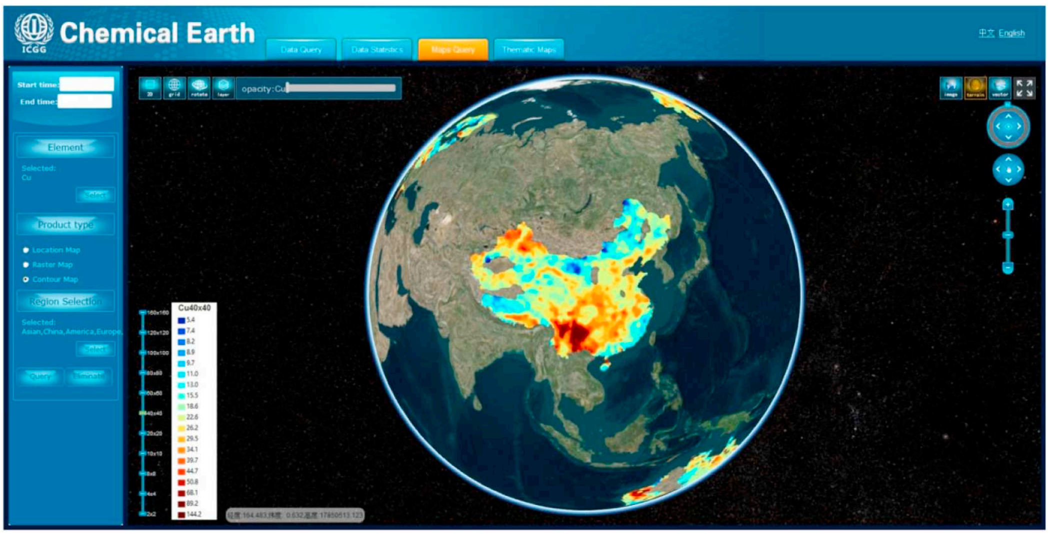

Fig. 6. Interface of the “Chemical Earth” platform.

5.2.2. Elements determined

The IGCP 259 project recommended 71 elements to be determined, which are divided into a high priority “List 1” (51 elements: Ag, As, Au, B, Ba, Be, Bi, C, Cd, Ce, Cl, Co, Cr, Cs, Cu, F, Ga, Ge, Hg, I, La, Li, Mo, N, Nb, Ni, Pb, Rb, S, Sb, Sc, Se, Sn, Sr, Th, U, V, W, Y, Zn, Zr, Al_2O_3, CaO, Fe_2O_3 (total), K_2O, MgO, MnO, Na_2O, P_2O_5, SiO_2, TiO_2), and a lower priority but potentially important “List 2” (20 elements: Br, Dy, Er, Eu, Gd, Hf, Ho, In, Lu, Nd, Pd, Pr, Pt, Sm, Ta, Tb, Te, Tl, Tm, Yb) groups (Darnley, 1995). However, except the CGB project and the China co-operation projects. The other projects finished by Australia, Europe and the USA have only determined 50–60 Elements. Some key elements for environment and health were not determined by any of the three projects such as Br, N and Carbon by the three projects (except C in EU and USA projects), even though they are included in “List 1”. Only thirty-five elements are common to all three projects: As, Ba, Be, Cd, Ce, Co, Cr, Cu, Ga, La, Mo, Nb, Ni, Pb, Rb, Sb, Sn, Sr, Th, U, V, W, Y, Zn, Zr, Al_2O_3, CaO, Fe_2O_3 (total), K_2O, MgO, MnO, Na_2O, P_2O_5, SiO_2, TiO_2, all of which belong to “List 1”. In order to establish a global geochemical database of permanent value, the report of IGCP 259 project recommendations for 71 elements of *environmental or economic significance* must be determined. It would be a great challenge for using these available data sets without some key elements for environment and health to generate a global geochemical baseline map.

5.2.3. Quality control

For obtaining harmonious global-scale data and quantifying or recognizing the future changes, tight quality control must be at every stage of the process. Analytical quality control includes international or inter-laboratory and inner-laboratory bias monitored by certified reference materials (CRMs), China Reference Materials and Canadian Reference Materials are recommended to be used for the laboratory quality (Darnley, 1995). But it is the greatest problem to be solved for preparation CRMs with at a least of 71 elements (Liu et al., 2015). For completed continental-scale geochemical mapping, in the NGSA project (Caritat and Cooper, 2011), five Certified Reference Materials were covertly inserted, however, among the 59 elements analyzed, the certified values of Ag, Bi, Cd, Cl, Dy, Ga, Gd, Ge, Ho, Pd, Pr, Pt, S and Sn in CRMs were not available. In the EU project, two CRMs were inserted (Salminen et al., 2005). But among 54 elements analyzed in EU project, standardized values in two CRMs for Dy, Er, Eu, Gd, Hf, Ho, Lu, Pr, Sm, Ta, Tb and Tm are not available. Exchanged CRMs have not been analyzed within the analytical stream of each project (Reimann et al., 2012a, 2012b). It is needed for assessment criteria of the data sets for the analytical variation among these elements without reference values of the CRMs. International Reference Materials with at least 71 elements certified need to be developed and necessary criteria that must be met for available data to go into a global baselines dataset are also needed.

6. Conclusions and discussion

The Mapping Chemical Earth, which is a big science program for mapping all chemical elements on the Earth, will experience a long-term implementation process just as other international scientific co-operation projects have experienced. Global geochemical baselines mapping has covered a total area of about 37 million km^2, nearly accounting for 27% of the global land till 2018 by different countries. The progress made in geochemical mapping has laid a solid foundation for establishing a global geochemical reference network and monitoring global chemical changes.

Comparing the data of China, the US, Europe and Australia, slight pollution of soils by toxic metals is the most serious in Europe, followed by the USA. Heavy pollution of soils by toxic metals are the most serious in Europe, followed by China. Australia has the lowest concentration of toxic elements. These observations may be due to the long industrial history of Europe and the rapid development and industrialization of the past 30 years in China. Comparing the datasets of 1994–1995 and 2008–2012 in China, the potentially toxic elements As, Cr, Cu, Hg, Ni, Pb and Zn, and particularly Cd in top soils significantly increase from 1990s to 2010s. We conclude that geochemical baselines using catchment sediment sampling can be applied to recognizing and quantifying the environmental changes induced by human activities or caused by natural processes.

It would be a great challenge for the available data sets by different countries using different sampling and analytical methods to generate a harmonious global-scale geochemical baselines map. Sampling methodologies and laboratory quality control for chemical analysis need to be standardized.

The ICGG would like to cooperate with the 192 Member States of UNESCO, the International Union of Geological Sciences (IUGS), the Coordinating Committee for Geoscience Programs in East and Southeast Asia (CCOP), the Association of Applied Geochemists (AAG), the IUGS Commission of Global Geochemical Baselines, the Eurogeosurveys, the Association of African Geological Surveys, etc. to establish a Global Geochemical Observation Network to provide chemical data for natural resource and environmental management.

CRediT authorship contribution statement

Xueqiu Wang: Supervision, Methodology, Writing - original draft.**Bimin Zhang:**Visualization, Data curation.**Lanshi Nie:**Data curation.**Wei Wang:**Data curation.**Jian Zhou:**Software, Methodology. **Shanfa Xu:**Data curation.**Qinhua Chi:**Investigation.**Dongsheng Liu:**Investigation.**Hanliang Liu:**Investigation.**Zhixuan Han:** Investigation.**Qingqing Liu:**Investigation.**Mi Tian:**Writing - review & editing, Conceptualization.**Baoyun Zhang:**Investigation.**Hui Wu:** Investigation.**Ruihong Li:**Investigation.**Qinghai Hu:**Investigation. **Taotao Yan:**Investigation.**Yanfang Gao:**Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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