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Geochemical Earth Reference Model (GERM): description of the initiative

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Abstract

The Geochemical Earth Reference Model (GERM) initiative is a grass-root effort with the goals of establishing a community consensus on a chemical characterization of the Earth, its major reservoirs, and the fluxes between them. The GERM initiative will provide a review of available scientific constraints for: (1) the composition of all major chemical reservoirs of the present-day Earth, from core to atmosphere; (2) present-day fluxes between reservoirs; (3) the Earth's chemical and isotopic evolution since accretion; and (4) the chemical and isotopic evolution of seawater as a record of global tectonics and climate. Even though most of the constraints for the GERM will be drawn from chemical data sets, some data will have to come from other disciplines, such as geophysics, nuclear physics, and cosmochemistry. GERM also includes a diverse chemical and physical data base and computer codes that are useful for our understanding of how the Earth works as a dynamic chemical and physical system. The GERM initiative is developed in an open community discussion on the World Wide Web (http://www-ep.es.llnl.gov/germ/germ-home.html) that is moderated by editors with responsibilities for different reservoirs, fluxes, data bases, and other scientific or technical aspects. These editors have agreed to lay out an initial, strawman GERM for their respective sections and to moderate community discussions leading to a first, preliminary

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consensus. The development of the GERM began with an initial workshop in Lyon, France in March, 1996. Since then, the GERM has continued to be developed on the Internet, punctuated by workshops and special sessions at professional meetings. A second GERM workshop will be held in La Jolla, CA USA on March 10–13, 1998.

Keywords: Transfer dynamics; Fluxes; Geochemical reservoirs; Residence time; Geochemical cycles; Differentiation of the Earth

1. Introduction

The understanding of the global chemical dynamics of the Earth requires a reasonably simple but comprehensive set of data on chemical inventories and fluxes. Ideally, such a data set may be formulated in terms of a reference model that includes a complete set of direct measurements that represent a very close approximation to the actual compositions. Such a chemical reference model is effectively impossible to establish for the Earth because most of the Earth is not accessible for direct observation. Nevertheless, even an imperfect chemical 'reference' model for the Earth would be a powerful tool for Earth system science, simply by providing the current best consensus, with estimates of uncertainties. Such a consensus would allow for coherent testing of global models, highlight gaps in our knowledge, trigger more focused work on the refinement of existing estimates, and make geochemistry more transparent to non-specialists.

Attempts to constrain the large-scale chemical composition of the Earth go back about 70 years to Victor Moritz Goldschmidt who established modern geochemistry as a field of research. He pioneered estimates of the large-scale chemical composition of the Earth's crust (Goldschmidt, 1933), and he probed the chemical relationships between meteorites and the silicate Earth (Goldschmidt, 1923, 1938). Another major step towards understanding the chemistry of the planet was made by Ringwood (1966) who proposed that the bulk of the mantle is made of 'pyrolite', a hypothetical mixture of ('depleted') mantle peridotite and basalt. Subsequently, the correlation between $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic compositions, combined with rare earth element abundance systematics demonstrated that the silicate Earth almost certainly was formed from material having the approximate composition of chondritic meteorites for many elements, and that the depleted mantle and the continental crust are two nearly complementary Earth reservoirs (DePaolo and Wasserburg, 1976; Richard et al., 1976; O'Nions et al., 1977).

Very important constraints for the chemistry of the Earth also come from global seismology, which is much further along with the establishment and use of a reference model. Jeffreys and Bullen (1940) and Bullen (1940) formulated the first density and seismic velocity profiles for the Earth. In 1971, Bullen established a Standard Earth Model Committee, which ultimately promulgated the Preliminary Reference Earth Model (PREM, Dziewonski and Anderson, 1981). PREM describes the one-dimensional density and seismic velocity structure for the Earth and it is now a fundamental reference in solid-Earth geophysics. The geophysics and mineral physics communities have developed and implemented procedures to review the now widely used PREM and to expand it into a more comprehensive geophysical model of the Earth (Navrotsky et al., 1995).

Three key aspects of PREM are relevant to the development of a Geochemical Earth Reference Model (GERM). (1) It must be accepted by a broad scientific community as the minimal consensus representation of some specific properties of the Earth (volumes, masses, density) to be used in different scientific fields, despite the fact that there is widespread recognition that it is incorrect in some details (e.g., spherical symmetry). (2) The relevant scientific community recognizes the need for a protocol to update the model. (3) The model provides a simplified representation of the Earth that can be passed to non-specialists, students, and the public without generating major objections from the 'expert' community.

The need for a Geochemical Earth Reference Model was identified as a major goal at the Mantle–

Ocean/Atmosphere (MOC) conference in August 1994 in Amsterdam (Staudigel et al., 1995) and led to the first GERM workshop in Lyon, in March 1996 (this volume). This contribution describes the background and the current state of the GERM Initiative.

2. Purpose of GERM

The present-day Earth is composed of a set of chemically distinct reservoirs with chemical fluxes between them. Fluxes between reservoirs fluctuate through geological time over a large range of time scales. These fluxes, and the resulting changes in reservoir compositions, established the 'Earth System' over its 4.5 Ga history and sustain its current habitability. The purpose of the GERM effort is to establish a community consensus on the chemical and isotopic inventories of these reservoirs and the chemical fluxes between them, both for the present Earth as well as through geological history. It will also establish values for fluxes averaged over different time scales (short-term fluctuations vs. secular trends). By combining GERM with PREM and other considerations of the physical Earth we will improve our understanding of how the Earth as a system has evolved through time. Thus, even if the community is not successful at establishing a complete and fully accurate chemical model of the Earth, the attempt itself will represent an important scientific exercise for geochemistry and will inevitably lead to further advances in our understanding of the Earth.

To be a useful global tool, GERM must characterize completely all reservoirs, even if some can only be established through indirect means. It is clear that for some reservoirs, our understanding will come almost completely from such indirect means (e.g., the lower mantle), and in these cases, it will be essential to establish a strategy for assessing and minimizing the uncertainties in our estimates of the chemical and physical characteristics (i.e., mass, volume, etc.). To be consistent, all major chemical and isotopic parameters must be reconciled with each other as well as with physical properties of the Earth. Each GERM entry must be characterized with respect to its type of estimate, associated uncertainties, potential variation in space and time, and it should be traceable to an original scientific publication.

Once established, GERM should facilitate progress in our understanding of a spectrum Earth science applications:

- It will become a tool to streamline and focus discussions on how the Earth works as a complete chemical system. Uniformly used assumptions (i.e., GERM) are necessary for a rigorous test of any system.
- It will allow simple determinations of the sensitivity of the Earth system to changing fluxes or environmental conditions.
- It will aid in understanding the long-term chemical and isotopic evolution of the Earth, and the behavior of short-term chemical cycles (e.g., the recent climatic record).
- It will highlight important gaps in our knowledge and identify future research needs for the refinement of the model.
- It may become a teaching tool in geochemistry and Earth system science education.
- It will allow specialists in all Earth science disciplines to work with one coherent data set for the chemical composition of major Earth reservoirs, aiding in the cross-fertilization between geophysical and geochemical communities.

3. Strategy for establishing the GERM

The status quo has not succeeded in uniting geochemists and geophysicists in their quest for a satisfying and complete physical, chemical, and isotopic characterization of the Earth. While a working model of the *physical* Earth is solidly in place (PREM), a *chemical* model is still in its infancy. The reasons for this include the inaccessible character of most of the Earth and the resulting difficulty of integrating constraints from myriad geological, geophysical, and geochemical data sets that are evolving rapidly. Because of the wealth of elements and their isotopic compositions, the number of geochemical parameters required to describe the GERM is extremely large. It is therefore clear that establishment of a GERM can succeed only if it is made a high priority community effort. Current efforts are focusing on the initial setup of a 'Preliminary GERM', which would be followed by a steady-state 'maintenance phase'. The procedure of setting up GERM will follow four stages:

3.1. Setup of an initial structure

An initial organizational task was the nomination of a steering group and editors for different components of the GERM, who have the responsibility for establishing a ‘Preliminary GERM’ that would be reviewed by a broader geochemical and Earth science community.

3.2. Initial model emplacement

In this stage, GERM editors determine the format and compile an initial, preliminary GERM data set to serve as a basis for a community discussion. Through this process, gaps are being identified that will need to be filled by using a variety of techniques, such as inferences based on mass balance considerations, cosmochemical arguments, geophysical constraints, or model calculations. At the end of the data-collection phase, these data will need to be checked for internal consistency, and sensitivity checks will have to be made to highlight critical problems. Constraints from the early Earth and the geochemical record will need to be integrated with the present-day model. Even though this initial data set will probably not be completed at the time of the next GERM workshop, it should outline the process by which a Preliminary GERM can be established. It will also present a large and centralized collection of to the broad scientific community for critical scrutiny, and serve as a basis for the discussion that will lead to a Preliminary GERM.

3.3. Establishment of the Preliminary GERM

The initial GERM data set will be discussed and screened at future GERM workshops. This effort will help define a procedure and a timetable for establishing a Preliminary GERM that can be recommended for broad-scale testing by the Earth science community. The product of this process, the preliminary GERM may be considered similar to the geophysical PREM, that has been in use for several years and is now being modified and updated on basis of new global data.

3.4. Continued refinement of GERM

Similar to PREM, continued and widespread use of the Preliminary GERM will reveal the need for modifications; it is inevitable that there will always be a need for future refinement. While it is important to discuss and consider improvements to the GERM, changes should be made only after a significant period of testing and use by the community.

The initial GERM workshop in Lyon, France, and a subsequent period of discussion resulted in completion of Stage I and work towards completing Stage II. At this time (November 1997), a significant data base has been accumulated on the GERM Web page, and this data base will continue to be updated by the editors in preparation of the second GERM workshop in La Jolla. In the long term, the GERM is intended to be structured as a database with editors, and organized like a hybrid of a scientific journal and a ‘Geochemistry Bulletin Board’ on the Internet. The intention is to combine the flexible and relaxed discussion format of a bulletin board with the demands for scholarly contributions in a refereed scientific journal.

4. The model

GERM centers on a chemical description of the present-day Earth reservoirs and the fluxes between them. Each inventory and flux may require a distinct treatment, for instance compilation of literature data, or generation of new data sets, or indirect evaluation for reservoirs that are inaccessible to observation. Definitions of reservoirs and fluxes have to consider the relevant time constants for chemical processes within a reservoir and transport between reservoirs. In the following sections of this report, we outline the major elements of each GERM component.

4.1. Germ reservoirs

The major goal of GERM is to divide the modern Earth into a complete set of geochemical reservoirs and provide an internally consistent set of data describing their chemical and isotopic composition.

Geochemically defined Earth reservoirs ultimately have to be reconciled with a physical definition and uncertainties of data need to be discussed. We recognize that these uncertainties will be large but we note that they often result from fluctuations in modal components, such as quartz in the continental crust or olivine in the upper mantle. In order to describe accurately the compositional diversity and to preserve information on covariations between elemental concentrations, a correlation matrix should be associated with each reservoir estimate.

4.1.1. Atmosphere / hydrosphere

Because of their accessibility, the gaseous and hydrous portions of the Earth are amongst the best known geochemical reservoirs and they are characterized by processes with the shortest time constants. The hydrosphere includes oceans, lakes, ice, and subsurface water within geological formations and hydrothermal systems. The goal of GERM is to provide links to standard atmospheric compositions, review chemical speciation and the primary controls on atmospheric composition, and to establish fluxes to and from other reservoirs. GERM efforts on the hydrosphere focus on the role of water in the transport of chemical elements, how this process controls the chemical inventory of hydrospheric reservoirs, the weathering cycle, climate, and the destruction and formation of chemical sediments.

4.1.2. Continental crust

The continental crust may be subdivided into upper, middle and lower crust, and continental sediments including shelf sediments. These sub-reservoirs constitute the cumulative record of continental growth, evolution and recycling. Equally important are the modern fluxes of continental growth occurring in areas of active volcanism (arcs, rifts and intraplate regions). These fluxes as well as the bulk composition of the continental crust is still poorly understood, despite the fact that it is the best exposed portion of the silicate Earth. ‘‘This is because the deeper crust is relatively inaccessible to direct observation and thus its internal make-up must be inferred from studies of lower crustal rock types that are typically out of context (i.e., granulite terrains and xenoliths at the Earth’s surface) as well as seismic velocities of the deep crust’’. Ultimately, the composition of the combined continental crust, oceanic crust, and the mantle must add up to a moderately outgassed bulk silicate Earth composition. Recent estimates of the composition of continental crust include in particular, tabulations by Taylor and McLennan (1985), Rudnick and Fountain (1995) and Wedepohl (1995).

4.1.3. Oceanic crust

Using the classical seismic definition of the oceanic crust, it can be subdivided into sediments, mafic crust and the underlying oceanic mantle (Layer I to III). Layer I can be relatively easily constrained by compositional data on the relatively large number of sediment drill cores recovered by the Deep Sea and Ocean Drilling Program, and the reasonably well understood global distribution of sediments (i.e., the recent compilations by Rea and Ruff, 1996 and Plank and Langmuir, 1997). Mid-ocean ridge basalts (MORBs) are widely studied from many mid-ocean ridges; nevertheless, there is some uncertainty about the composition of the deeper crust and of primitive MORB melts. Major uncertainties exist about the bulk composition of matured, altered oceanic crust as it is recycled at subduction zones. Our current approach is to measure bulk compositions in well recovered drill holes into the oceanic crust and to derive enrichment/depletion factors for the alteration of ophiolitic rocks. These factors can then be applied to unaltered MORB compositions to estimate an average bulk composition for ‘mature’ oceanic crust (Staudigel et al., 1996).

4.1.4. Mantle

Samples of the lithospheric mantle are available for direct observation in the form of inclusions in mantle-derived magmas, peridotite massifs and ophiolites, and this portion of the mantle will be estimated from the composition of such samples. However, the chemical composition of the sources of most mantle-derived magmas, such as MORBs and OIBs, can only be inferred through modeling of the melting process. Our goal is to provide estimates of the isotopic and chemical compositions of the portions of the mantle that are available for direct measurements or through modeling of the melting process that gives rise to primary mantle-derived magmas.

4.1.5. Core

It is well established that the Earth's core is primarily composed of iron. Many proposals have been made for additional element(s) in the core, however, there is as yet no general agreement on this issue. Our goal is to provide a composition for the core that is consistent with element abundance patterns measured in meteorites and the silicate portion of the Earth, as well as mass balance considerations.

4.2. GERM fluxes

Many fluxes between Earth reservoirs can be measured directly; others need to be inferred. The goal is to evaluate the magnitude of the fluxes and their fluctuations over relevant time scales ($\sim$ 1000 years to 1 billion years). The shorter time-scales will provide a natural connection with the various Global Change Initiatives. Global balancing of the fluxes is not required unless there is compelling evidence that some reservoir subsets operate at steady-state over the time scale of interest.

4.3. The geochemical evolution of the Earth

We have incomplete and arguable indications that the chemical composition of some of the major geodynamic units may have changed since the Archean (e.g., felsic and intermediate volcanic rocks and chemical and clastic sediments in the continental crust, ocean floor basalts, seawater composition). Estimates of Archean and Proterozoic compositions for the crust, sediments, and basalts will therefore be made part of the GERM data base. The geochemical evolution of the Earth and many of its major reservoirs can be constrained through radiogenic isotope systematics. The initial state of the Earth is the essential starting point for all evolutionary models of reservoirs in the Earth. The isotopic compositions and elemental abundance patterns in meteorites and the sun, as well as the Earth's present bulk composition provide important information on the basic building blocks available for the Earth during its accretion phase. Processes that continue to operate in the modern Earth and that have billion-year time-scales can only be understood by looking at the record of isotopic changes in the solid Earth reservoirs over geologic time. In particular, the geologic history of chemical and isotopic variations of seawater, as recorded in fossils and inorganic chemical sediments, provide important information about global geochemical fluxes throughout the Phanerozoic and into the Archean (once diagenetic distortion of the signal is removed). Deciphering these records can provide important clues about the nature and magnitude of geochemical fluxes during geological history, particularly with respect to different climatic conditions, variations in the extent of volcanic activity, and varying intensity of tectonism.

4.4. Other data

GERM also serves as a source for supplementary data, useful graphics and computing tools in geochemistry. Supplementary data may relate directly to the estimates of GERM reservoir compositions, partition coefficients, or other useful numbers and data that help in understanding the chemical composition and diversity of the earth.

5. Community involvement

The success of GERM is critically dependent on the geochemical community at large, as a resource for globally relevant data and because a community consensus needs to be reached on the merit of GERM entries. For this reason, community contributions are necessary and welcome. Such contributions may take the form of data that fill gaps in GERM or by critical commentary on particular entries. Comments and contributions may be directed to the GERM steering group, and or to the relevant editor of a particular reservoir or other section of GERM.

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