UCRL-JC-126054
PREPRINT

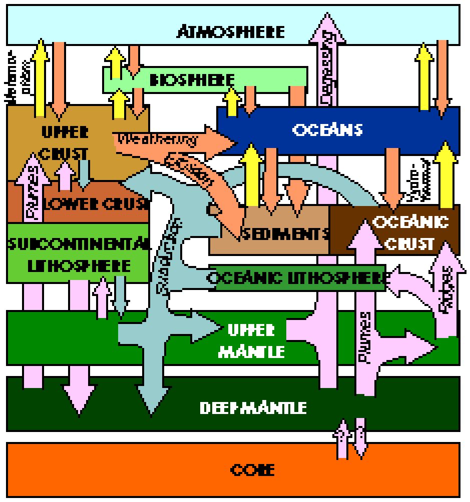
The Geochemical Earth Reference Model (GERM)

H. Staudigel
F. Albarede
H. Shaw
B. McDonough
W. White

This paper was prepared for submittal to the
American Geophysical Union Fall Meeting
San Francisco, CA
December 16-20, 1996

December 1996

THE GEOCHEMICAL EARTH REFERENCE MODEL (GERM)



by

Hubert Staudigel, Vrije Universiteit Amsterdam, now at Institute for Geophysics and Planetary Physics, UCSD-0215, La Jolla, CA 92117-0225

Francis Albarede, Ecole Normale Superieure de Lyon, 46 Alle d'Italie 693647 Lyon CEDEX 7, France

Henry Shaw, Lawrence Livermore National Laboratory, Geosciences and Environmental Technologies Division, L-201, Livermore, CA 94550

Bill McDonough, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford St., Cambridge MA 02138

William White, Dept. of Geology, 2122 Snee Hall, Cornell University, Ithaca, NY 14853

and the GERM editors:
albarede@geologie.ens-lyon.fr, Mcdonough@eps.harvard.edu, white@geology.cornell.edu, shaw4@llnl.gov, derry@geology.cornell.edu, edmond@mit.edu, jacobsen@neodymium.harvard.edu, langmuir@ldeo.columbia.edu, lasaga@quantm.geology.yale.edu, oconnell@geophysics.harvard.edu, tplank@kuhub.cc.ukans.edu, rudnick@eps.harvard.edu, shirey@dtm.ciw.edu, zindler@magnet.fsu.edu

Abstract
The Geochemical Earth Reference Model (GERM) initiative is a grass-root effort with the goal of establishing a community consensus on a chemical characterization of the Earth, its major reservoirs and the fluxes between them. The long term goal of GERM is a chemical reservoir characterization analogous to the geophysical effort of the Preliminary Reference Earth Model (PREM). Chemical fluxes between reservoirs are included into GERM to illuminate the long term chemical evolution of the Earth and to characterize the Earth as a dynamic chemical system. In turn, these fluxes control geological processes and influence hydrosphere - atmosphere - climate dynamics. While these long term goals are clearly the focus of GERM, the process of establishing GERM itself is just as important as its ultimate goal.

The GERM initiative is developed in an open community discussion on the World Wide Web (GERM home page is at http://www-ep.es.llnl.gov/germ/germ-home.html) that is mediated by a series of editors with responsibilities for distinct reservoirs and fluxes. Beginning with the original workshop in Lyons (March 1996) GERM is continued to be developed on the Internet, punctuated by workshops and special sessions at professional meetings. It is planned to complete the first model by mid-1997, followed by a call for papers for a February 1998 GERM conference in La Jolla, California.

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. Attempts to establish an Earth reference model go back more than 55 years when Jeffreys and Bullen (1940) and Bullen (1940) formulated the first density and seismic velocity profiles for the Earth. This led to the first concepts of the Earth being chemically made up mostly of meteoritic material (Ringwood, 1966) . The geophysics community recognized very quickly the need for an Earth reference model, resulting in the establishment of the Standard Earth Model Committee under Keith Bullen in 1971. Ten years later Dziewonski and Anderson (1981) proposed a “Preliminary Reference Earth Model” (PREM), describing the one-dimensional density and seismic velocity structure for the Earth. PREM is now a fundamental reference in solid-Earth geophysics and provides a widely accepted reference state for a variety of geophysical and geochemical applications, including mantle tomography, mantle chemical geodynamics.. Three key aspects of PREM are that (1) it is accepted by the broad community as a 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 detail (e.g., spherical symmetry), (2) the geophysical community recognizes the need for an updating protocol (3) PREM provides a simplified representation of the Earth that can be passed to non-specialists, the students, and the broad public without generating major objections from the geophysical community.

Our first understanding of the chemical constitution of the Earth was based on the correspondence of its density structure with distinct meteorite classes: the density of the core is similar to that of iron meteorites and the density of the silicate portion of the Earth is similar to that of stony meteorites. Ringwood (1966) put forth some of these concepts. Since then there have been many attempts to characterize specific Earth reservoirs, but there was no credible attempt to establish a community consensus on the chemical structure and inventory of the entire Earth until recently. In March 1996, F. Albarede, W. White and H. Staudigel convened a workshop in Lyon, France, intended to initiate an effort to establish a Geochemical Earth Reference Model (GERM). At this workshop, it was argued that the establishment of a GERM is feasible, despite the fact that, chemical parameters of the deep interior Earth cannot be directly measured as can, for example, the velocity structure of the Earth. Thus, the “geochemical Earth” is much less well understood than the geophysical Earth. Analogous to PREM, GERM is envisaged as an ongoing development effort aimed at establishing a current community consensus on the composition of the Earth, the size and composition (both chemical and isotopic) of its constitutive reservoirs as a function of time, the fluxes between reservoirs over different time scales, and the uncertainties in these estimates. There are many uses for a GERM, even if it is partly based on indirect estimates, guided by the existing, but incomplete set of chemical and physical measurements and models. GERM is a vehicle by which to combine individual efforts to characterize parts of the earth into a complete chemical system that would be consistent both internally and with respect to PREM and other geophysical constraints. In summary, we believe the primary goals for the GERM effort are: 1) to develop a greater understanding of global chemistry; and 2) to provide a platform for a more focused discussion of geochemistry in the context of earth system science.

At the Lyons workshop, participants set up an initial steering group for the GERM effort. The World Wide Web (WWW) was chosen as the primary platform for development of the first draft of a preliminary GERM (http://www-ep.es.llnl.gov/germ/germ-home.html). Web publication is to be supplemented by conventional papers to be published in a special volume of *Chemical Geology*. Following the workshop, a series of draft GERM documents were posted to the WWW to stimulate thinking and discussion among the members of the steering group and other interested parties. This effort will culminate in a special session at the Fall 1996 AGU meeting, at which the structure, format, and outline of the content of a first draft of GERM will be presented. At the AGU meeting, a final steering group will be established and a structure laid out that will lead to Preliminary GERM, analogous to PREM.

Purpose of GERM

The present-day Earth is composed of a set of chemically distinct reservoirs with chemical fluxes between them. Fluxes between reservoirs vary greatly in magnitude both as a function of the time-scale considered as well as through geological time. These fluxes, and the resulting changes in reservoir compositions, established the “System Earth” over its 4.5 Ga history and sustain its current habitability. The purpose of GERM 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 and also for different time scales (short-term fluctuations vs. secular trends) Defined in this way, it is clear that establishing a GERM is a (some might argue **the)** key objective for the field of geochemistry. 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 credible chemical model of the Earth, the attempt itself represents one of the most important scientific exercises in geochemistry and will inevitably lead to further advances in our understanding of the Earth.

To be successful, GERM must have several attributes:

- To be a useful global tool, it must characterize completely *all reservoirs*, even if some can only be established through indirect means. Whenever this task turns out to be daunting (e.g., lower mantle), a strategy to assess and minimize the uncertainties should receive topmost priority.
- 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 with length- and time-scales, and be traceable to an original scientific contribution.

Once established, GERM should facilitate additional progress in developing our understanding of the Earth through its use in a broad spectrum of 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 determination 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, as well the short-term chemical cycles (*e.g.,* the recent climatic record).
- It will allow Earth system scientists of different disciplines to work with one coherent data set for the chemical composition of major Earth reservoirs, aiding in the cross-fertilization between these and a wider spectrum of geophysical and geochemical communities.
- It will aide us in identification of important gaps in our knowledge and identification of future research needs for the refinement of the model.

Overall, GERM will provide a focus for the continued processing of geochemical information into our larger base of Earth system science, and hence continuous refinement must be accepted as an intrinsic component of GERM. Changes, however, should be made only after a significant period of testing and use by the community of each published revision. We envision that the Model will not evolve continuously, but rather, follow a course of "punctuated equilibrium".

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 system. While a working model of the physical Earth is solidly in place (PREM), a chemical model is still in its infancy. 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. It is therefore very clear that establishment of 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 has to follow a logical series of four stages; the process is currently in Stage II:

I SETUP OF AN INITIAL STRUCTURE

An initial organizational task was the nomination of a steering group, which had the responsibility for establishing a "Preliminary GERM" that would be reviewed by a broader geochemical and Earth science community. The steering group assigned specific responsibilities to its members: *e.g.*, characterization of specific reservoirs or fluxes and the correlation of these data with each of the other reservoir data sets. In addition, the steering group recognized the need to develop multiple platforms (hard copy and electronic) for publication of the results and to facilitate discussion in the Earth science community.

II INITIAL MODEL EMPLACEMENT BY THE STEERING GROUP

To establish the format and content of the "Preliminary GERM" an initial set of inventory and flux are being compiled from the literature and unpublished work. These data are being published on the World Wide Web as they are become available. This work is being conducted by steering group members and other scientists on a volunteer basis. Through this process, gaps are being identified that will need to be filled by using a variety of techniques, such as mass balance, 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. After completion, this model will be made available to the broad scientific community for critical scrutiny.

III ESTABLISHMENT OF THE PRELIMINARY GERM

Together with publication of the Preliminary GERM, there will be a call for a second GERM workshop to be held at Scripps (UCSD/SIO) in early 1998. This workshop will serve as a forum for conducting a broadly based screening of the Preliminary GERM, and to discuss and improve estimates of poorly constrained fluxes and reservoir compositions, as well as improvements to better known estimates.

The final result of this workshop will be a GERM analogous to PREM, but it will identify important gaps and weaknesses, as well as the sensitivity of GERM to them. These weaknesses and potential calls for future studies will be documented in a "White Paper" that will be supplied to major global initiatives, such as CSEDI, ODP, JGOFS, and RIDGE, in addition to funding agencies. This will establish linkages to these initiatives and strengthen their global geochemical focus.

IV CONTINUED REFINEMENT OF GERM

Similar to PREM, continued use of 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 GERM, changes should be made only after a significant period of testing and use by the community.

Current Status and Plans

The initial GERM workshop in Lyon, France, and a subsequent period of discussion resulted in completion of Stage I above and work towards completing Stage II. An important result of our special GERM session at the Fall 1996, AGU meeting will be the establishment of a plan for finalizing Stage II. In this section, we outline the structure of the model, name the individuals responsible for developing certain sections of the model, and discuss the current products of our efforts on the World Wide Web.

GERM ORGANIZATION:

In absence of direct funding, GERM has been a grass-roots effort of individuals who volunteer their efforts. For this reason, it is difficult to establish rigorous deadlines, and most of the individuals contribute as their schedules permit. However, the overall success, so far, is significant, with respect to momentum and progress.

While the initial setup of GERM critically depends on the effort of key individuals putting up various "Preliminary" models, in the long term, GERM is intended to be structured data base with editors, although 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.

GERM was initiated in response to a call for workshops of the European Association of Geochemistry, and currently operates loosely in this sense, without any formal control by any of our professional societies. Once the setup period is completed, GERM will be embedded in the structure of the Geochemical Society, and possibly other Earth science societies or global initiatives.

A GERM home page has been set up on the World Wide Web and the Preliminary GERM is being continuously developed and updated during this early genesis stage. This will make the process transparent to each interested member of the Earth science community, and allow for input. However, our experience to date shows that the number of contributors is small and they are essentially all part of this effort anyway. Most of the compilation of GERM data to date has been based on individual efforts. After an initial period of data collection, there will be a need for a small workshop amongst steering group members for discussing the results and the procedure for drafting a preliminary GERM.

The Model:

GERM centers around the major reservoirs and the fluxes between them for the modern Earth. Each inventory and flux may require a distinct treatment; compilation of literature data, generation of new data sets, and even indirect evaluation for the reservoirs that are inaccessible to observation. In the following we outline the major sections of GERM, their mission statements and editors responsible for pulling together each data set.

1. GERM Reservoirs

Mission Statement: The goal is to divide the earth into a set of modern reservoirs, and provide an internally consistent set of data describing their chemical and isotopic inventories (*i.e.*, the masses of the reservoirs and their chemical and isotopic compositions). We have established some working model compositions (e.g., Figures 1 and 2) for these reservoirs and these working models are presently posted on the Internet at the GERM web site.

Mission Statement: The goal is to divide the Earth into a set of modern reservoirs, and provide an internally consistent set of data describing their chemical and isotopic inventories (*i.e.*, the masses of the reservoirs and their chemical and isotopic compositions).

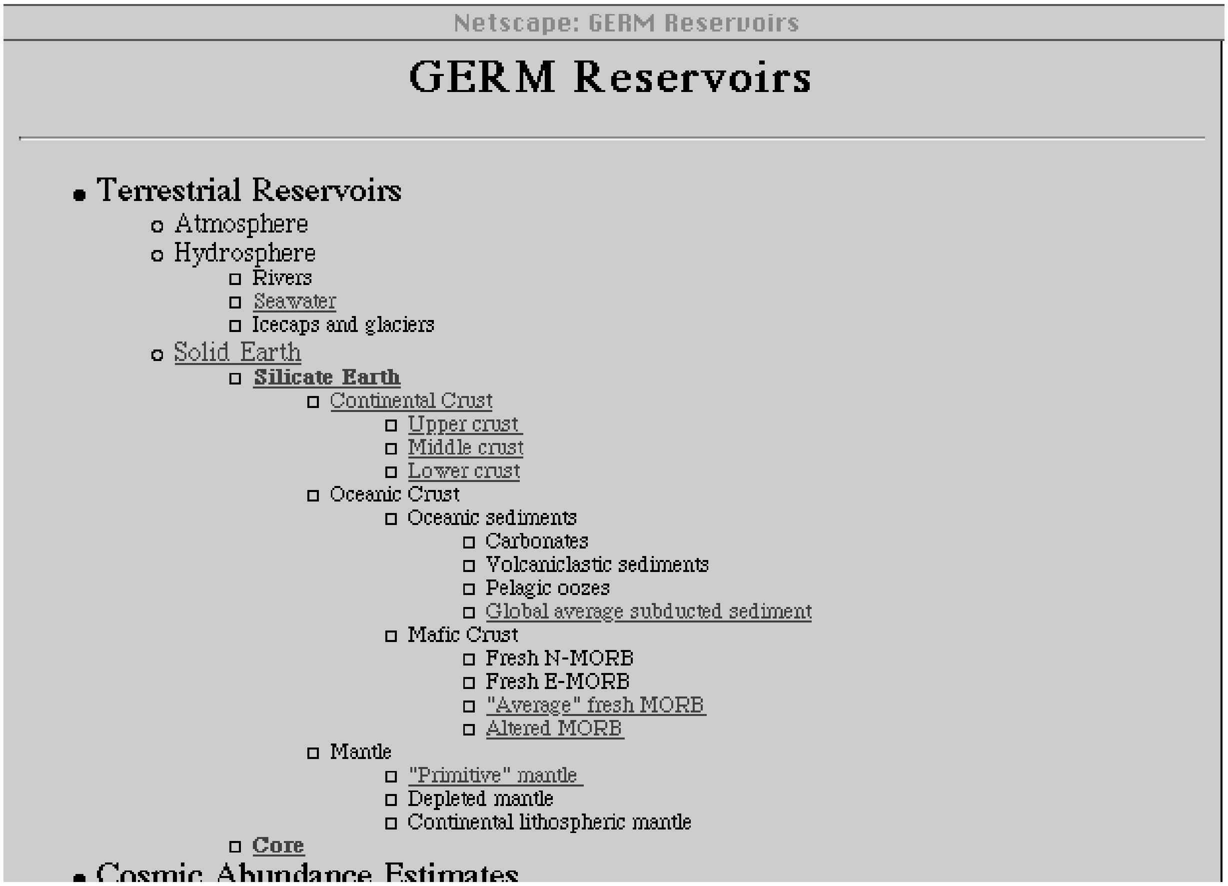


Figure { SEQ Figure * ARABIC }. WWW site listing of the GERM Reservoirs. Some details of reservoir identifications are still under discussion.

Netscape: GERM Periodic Table

GERM -- Reservoir Composition Data (by element)

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																		
1	1 H																1 H	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	* La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	** Ac-Lr	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
-																		
*Lanthanides			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
**Actinides			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

Figure { SEQ Figure * ARABIC }. WWW site listing of the GERM Reservoir compositions by element.

2A. GERM FLUXES (McDonough):

Mission Statement: 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 typical time- scales, typically from 1000 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 compelling observations indicate that some reservoir subsets operate at steady-state over the time-scale of interest. Long-term (secular) changes through the geological past will receive a separate treatment (see below). The matrix below indicates schematically the major fluxes that we anticipate will be a part of GERM. Note that each of the major fluxes may involves several independent mechanisms, each with its own flux that will ultimately require quantification.

Reservoir	Inventory Editor	Input to: Atmosphere	Hydrosphere	Continental Crust	Oceanic Crust	Mantle	Core
Atmosphere	?		rain, gas exchange	weathering	-	-	
Hydrosphere	Edmond	evaporation aerosols	runoff, water column processes	weathering	low-T alteration	subduction	
Continental Crust	Rudnick	weathering outgassing	weathering	metamorphism igneous activity	mechan erosion atmospheric dust	subduction delamination	
Oceanic Crust	Langmuir/Plank/Staudigel	-	low-T alteration	tectonics	-	subduction	
Mantle	Zindler/Jacobsen	Outgassing, aerosols	Outgassing, Hydrothermal activity	magmatism	ridge process, intra-plate volcanism	plumes and subduction	D" - core interaction
Core	McDonough					D" - core - interaction	

Table 1. Top-level structure of GERM fluxes

2B. EARLY EARTH (Jacobsen)

Mission Statement: There is much that can learned through the study of the Earth's early geochemistry. Relating the early Earth to accretion models provides constraints about the formation of the Earth and constrains its bulk chemical and isotopic composition. The evolution from early to present-day Earth provides a baseline for chemical fluxes between reservoirs through geological time. Many aspects of "Early Earth GERMs" will be much less well constrained than the present-day GERM, but even limited data sets (such as radiogenic isotopes) will help constrain critical elemental abundance ratios, and initial isotopic conditions.

2C. The Geochemical Record (Veizer)

Mission Statement: The geologic history of chemical and isotopic variations of sea water as recorded in fossils and inorganic chemical sediments may 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 for the nature and magnitude of geochemical fluxes during very different periods of geological history, particularly with respect to different climatic conditions, variations in the extent of volcanic activity, and varying intensity of tectonism. The major contribution of this portion of GERM is will be to provide estimates of the changes in magnitude (or even sign) of relevant fluxes in response to particular geological activities or events. Such information has potentially important implications for our understanding of climate change.

Useful Information

The WWW version of GERM also has sections with various useful data or models. The intention is to provide a useful compilation of data and computer codes as a teaching and research aide to the community.

In particular, we will establish:
- a database for mineral-melt and mineral-aqueous fluid partitioning
- a compilation of common physical parameters useful for modeling
- an on-line archive of supplementary or "backup" data that were used to derive the parameter estimates in GERM

- a list of references used in GERM
- a compilation of references that are useful for in-depth analysis of various GERM topics
- computer codes for standard modeling applications, typically box and convective-diffusive models

In particular the last item is intended as a service for individuals who wish to publish computer codes as "shareware"

The combination of all of the above will foster the use of GERM as a teaching tool, whereby students may be asked to use specific programs and data bases to carry out state-of-the-art modeling exercises.

Timetable

Following the recommendations during Fall AGU 1996, we propose the following tentative time table:
- Jan. - June 1997: Establishment of first complete data base for the GERM
- June 1997: Editor-conference at Goldschmidt 1997.
- Publication of the first draft of the preliminary GERM and final announcement of a GERM workshop at SIO in Feb. 1998, call for papers with an abstract deadline of Dec. 1, 1997.
- Feb./March 1998 GERM conference at Scripps, convened by H. Staudigel and G. Masters (SIO-IGPP), W. McDonough (Harvard), and A. Lasaga (Yale), on behalf of the GERM steering committee and its editors
- Summer 1998 publication of Preliminary GERM and beginning of steady state of GERM modification and testing.

Community Involvement

As indicated in earlier sections of this document, the success of GERM is critically dependent on the involvement of the geochemical community en large. At any stage of the setup of GERM community input is welcome. Please direct your comments (preferably by E-mail) to any member of the GERM team (E-mail addresses above), with a cc to H. Staudigel.

References:

Bullen, K.E., 1940, The problem of the Earth's density variation. Bull. Seis. Sic. Amer., 30, 235-250

Dziewonski, A. M. and D.L. Anderson, 1981, Preliminary Earth Reference Model, Phys. Earth Planet. Inter., 25, 297-356.

Jeffreys, H. and Bullen, K.E., 1940, Seismological Tables. Brit. Ass.Gray-Milne Trust.

Ringwood, AE, 1966, Chemical evolution of the terrestrial planets. *Geochim. Cosmochim. Acta*, **30**, 41.

This work was performed under the auspices of the U.S. dept. of Energy at LLNL under contract no. W-7405-Eng-48.

Technical Information Department **• Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551