RESULTS FROM PRIOR NSF SUPPORT

R. Jeanloz, P.I., *"Composition and Evolution of the Lower Mantle: Experiments on the Thermal Equation of State of Perovskitite"* (7/1/96-6/30/99; $132,638); *"Experimental Study of Water at Deep-Earth Conditions"* (6/15/00-5/31/02; $179.835)

Recent work partially or fully funded by NSF has included documenting the high-pressure mineral assemblage of natural samples of peridotite and mid-ocean ridge basalt (MORB) at lower-mantle pressures (both at high temperature, and after quenching to room temperature); determining the 3-D temperature distribution inside the laser-heated diamond cell through a combination of modeling and measurement; and characterizing the effect of high temperatures and pressure on water and oxygen.

Selected Recent Publications: Funamori, et al. (2000), Panero and Jeanloz (2001a,b; 2002), Jeanloz (2001), Benedetti et al. (2002), Panero et al. (2002a,b).

Mark Bukowinski, PI. NSF EAR-0114304. Project: Structure and Thermoelastic Properties of Al- and Fe-bearing High Pressure Silicate Minerals; $240,000; 1/1/01-12/31/03.

We have successfully applied the highly efficient (orders of magnitude faster than first-principles approaches) Variationally Induced Breathing (VIB) model of ionic interactions, based on local density electron gas energy functionals, to study the structures and equations of state of numerous minerals believed to constitute the Earth's mantle (Bukowinski, 1994; Bukowinski et al., 1997; Downs and Bukowinski, 1997; Bukowinski and Downs, 2000; Akber et al., 2002). Under the present grant we have added a pseudoempirical correction to VIB to improve the treatment of the partly covalent Si-O bond. Taking advantage of the flexibility and efficiency of VIB, we have started computations on the effects of small concentrations of Al, Fe and Ca in MgSiO3 perovskites, and we are examining the possibility that the latter may undergo subtle changes in its structure within the deep mantle.

Selected recent publications: Bukowinski et al. (1997), Downs and Bukowinski (1997), Bukowinski and Downs (1997, 2000), Akber et al. (2002).

M. Manga, P.I., *CAREER development in geological and environmental fluid mechanics*, EAR-9701768 ($235,665) 09/1997-06/2002. *Obsidian flow emplacement*, EAR-9805305 ($32,931), 06/1998-05/1999.*Rheology of bubbly magmas and lavas*, EAR-0003303 ($78,945), 01/2001-01/2003. *Experimental investigations of the dynamics of thermochemical boundary layers in the mantles of terrestrial planets*, EAR-0124972 ($287,251), 01/2002(anticipated)-01/2005.

These 4 grants (Manga, PI) have supported 9 graduate students, 1 postdoc, 3 undergraduates, and 2 visiting graduate students working in the broadly defined area of geological and environmental fluid mechanics: Liz James (isotope hydrology of springs in the Oregon Cascades), Martin Saar (permeability of vesicular basalts, groundwater flow in the Cascades), Chad Dorsey (particle size segregation in avalanches), Dayanthie Weeraratne, Mark Jellinek and Helge Gonnermann (mantle convection), Bretagne Hygelund (hydraulic effects of woody debris), Alison Rust (rheology of multiphase fluids), Jon Castro (obsidian flow emplacement), the lab experiments of Julia Hammer (eruption mechanics), Jan Stark (bubbles in porous materials) and Nathanael Schaeffer (mantle plume dynamics).

The CAREER grant has also supported the development of hands-on teaching materials (mostly in the form of laboratory exercises) for a class on geological fluid mechanics. In 1999 the PI received the Ersted Award for Distinguished Teaching, reflecting the success of the fluid mechanics class.

Publications supported by these grants (see proposal reference list):Manga (2001a), Saar et al. (2001). Manga et al. (2001), Schaeffer and Manga(2001), Manga and Loewenberg (2001), Manga(2001b), James et al. (1999, 2000a, 2001), Manga and Kirchner (2000), Stark and Manga

(2000), Manga and Weeraratne (1999), , Manga (1999), Saar and Manga (1999), Manga et al. (1998), Manga (1998a,b), Hammer et al. (1998), Dorsey and Manga (1998), Weeraratne and Manga (1998), Montague et al. (1998), Manga (1997), Manga and Jeanloz (1997), Castro et al. (2001), Gannett et al. (2001), Rust and Manga (2001), Hygelund and Manga (2001), Hunt and Manga (2001), Jellinek and Manga (2001), Brodsky et al., 2001.

B. Romanowicz. (P.I.), *Studies of the CMB and inner core using body waves and free oscillations* EAR-9417862 (3/95-2/98) $181,472 *High resolution modeling of the core-mantle boundary region and the inner core* EAR-9902777 (8/99-7/02) $220,000. *Global attenuation model of the whole mantle using waveform tomography* EAR-9706380 (09/01/97-12/31/99), $140,000. *3D Variations in temperature and composition in the upper mantle* EAR-0001955, (8/00-8/01), $19,391 to UMN, EAR-0001965 $27,703 to UCB, collaborative with S.Karato.

These grants has supported work on several problems of deep earth structure: (1) anisotropy in the inner core using PKP travel time and attenuation data, as well as free oscillations splitting measurements; (2) structure of D" from observations of S-diffracted waves at long ranges as well as PKP travel times. (3) Global mantle tomography, in particular attenuation tomography, introducing a waveform modeling approach. The last grant has supported a pilot study to prepare the ground for mapping out three-dimensional variations of temperature and water content in the earth's upper mantle directly from seismic waveform data.

Publications supported by these grants (see references at end of proposal): Bréger and Romanowicz (1998), Bréger et al. (1998), Durek and Romanowicz (1999), Romanowicz et al. (1996), Souriau and Romanowicz (1996a,b) Vinnik et al. (1995; 1998a,b), Bréger et al. (1999, 2000a,b, 2001), Romanowicz and Bréger (2000), Tkalcić et al. (2001), Tkalcić and Romanowicz (2001). Li and Romanowicz (1995, 1996); Mégnin and Romanowicz (1998, 2000); Mégnin et al. (1999), Romanowicz (1998), Romanowicz and Durek (2000), Gung and Romanowicz (2001), Romanowicz (2001), Karato (2001), Gung et al. (2001).

D. DePaolo, P.I. U-Th-Pb geochronology and mineral Pb systematics of Quaternary basalt NSF EAR 9909590, $189,717 (1/1/00-12/31/01); *Reaction lengths and reaction rates in metamorphic rock systems using isotopic and age zoning in garnet porphyroblasts*, NSF EAR9805218, $125,022 (6/1/98-12/31/00).

These grants have supported work on: (1) evaluating high precision Pb isotopic compositions, coupled with U, Th, Pb concentrations to determine dates for Quaternary volcanic products, especially basalts. We are also investigating the utility of high precision Pb isotopes in more silicic systems to track magmatic processes. (2) measurement of Rb-Sr and Sm-Nd isotopes in garnet porphyroblasts, other minerals, and whole rocks samples near contacts between High Rb/Sr and low-Rb/Sr rocks units in metamorphic rocks in the Alps of Switzerland and in Vermont. Parallel measurements were made on Ar-Ar systematics of biotites and other minerals in the same transects. The results were used to estimate the rates of metamorphic reactions, and the bulk diffusivity of Sr, Nd, and Ar in the rocks during the metamorphism.

Publications (See proposal reference list): DePaolo et al. (2001), DePaolo and Daley (2000), Jellinek and DePaolo (2002), Sims et al. (submitted), Hammersley et al. (2001), Bryce and DePaolo (in prep.); Baxter and DePaolo (2000, 2002a,b), Baxter et al. (2002a,b).

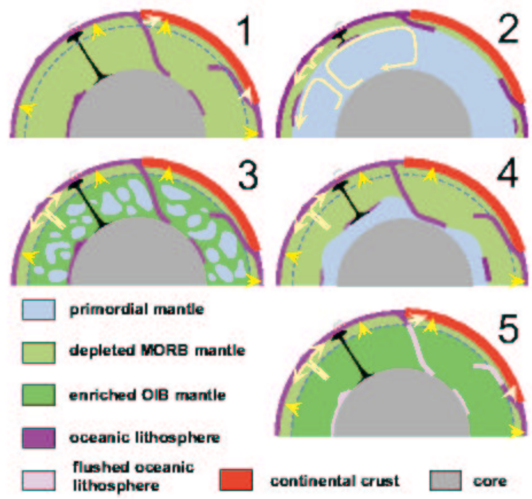

Figure 1: Different conceptual models of mantle circulation, as compiled by Albarède and van der Hilst (1999).

1) INTRODUCTION

It has been 35 years since the acceptance of plate tectonics theory, but no definitive agreement has yet been reached among geoscientists on the fundamental nature of the global dynamic processes that drive plate motions. There are still vigorous debates about the proportion of heat coming from the core, versus radiogenic heating in the mantle, about the degree to which the 670 km discontinuity impedes whole mantle circulation, about the origin of mantle plumes, the chemical/thermal nature of heterogeneity in the deepest mantle, or the nature and importance of coupling between the mantle and the core. (e.g. Figure 1)

Moreover, each of the disciplinary communities appears to have adopted a favorite set of assumptions, based largely on their limited view of the problem as afforded by their own discipinary observations, and on their limited understanding of the capabilities and limitations of other disciplines.

In the meantime, tremendous progress has been made in these different fields in the quality and quantity of data collected, for example through the IRIS program in seismology, through state of the art analytic facilities in geochemistry, advances in computational technology in geodynamics, or through access to advanced accelerator facilities in mineral physics. The situation reminds us of that of the famous story about the elephant and the group of blind fellows, each of whom had an accurate but divergent view of the animal based on their ability to explore a leg, an ear or the trunk.

It is becoming increasingly clear that significant progress in our understanding of the fundamental global scale dynamic processes of the Earth's interior can only be achieved through an integrated, multi-disciplinary approach, combining knowledge and latest achievements in each of the following disciplines: seismology, geodynamics, mineral physics, geochemistry and geomagnetism.

Through major infrastructure efforts that are currently under way, or in the planning stages, a new generation of disciplinary tools will soon be available to the geoscience community, that will provide unprecedented new observations on the earth's interior. For example, Earthscope, and more specifically the USArray program, will provide seismologists with a high resolution "window" into the deep mantle and core through the acquisition of dense broadband seismic waveform data over the north American continent. The COMPRES program will allow mineral physicists to perform the most advanced high pressure (high temperature) measurements on mineral properties at conditions relevant to the Earth's deep interior. Other initiatives aim at providing geodynamicists with a unified, state of the art framework for convection computations, seismologists with ocean-bottom stations in order to achieve truly global coverage of the earth, and researchers in geodesy and geomagnetism with satellite observations that will revolutionize these fields. It seems that our community has been building "big-science" data gathering tools but uses only "small-science" approaches to data interpretation. As a result, only partial return on these investments can be expected. In other fields of science, such as astronomy or atmospheric sciences, this has been realized for quite a while.

Yet, truly interdisciplinary work remains a formidable challenge in solid Earth geophysics. The CSEDI program, launched about ten years ago (O'Connell et al., 1993), holds promise for groups of individual investigators to address specific research problems jointly among two or more disciplines, as has been demonstrated in the last few years (e.g. Figures 2, 3). Nevertheless, there is a crying need for a major leap in the level of research collaboration and education of scientists across fields.

To some extent, Gordon Conferences on the Earth's interior, reinstated in the past 5 years, and the biennial international SEDI Conferences, provide forums for the exchange of information and latest ideas across the different disciplines. They are, however, short-lived, covering all possible topics in just a few days, and therefore can provide only glimpses into other fields for specialists of any given discipline.

What is needed is a long-range intellectual framework that will allow a more effective cross-fertilization of the different disciplines, whereby senior and junior scientists alike can be thoroughly educated about the approaches, the fundamental achievements, the future potential and limitations of the "other disciplines", in order to gain a common language. Given the enormous amount and diversity of observations becoming available across the relevant disciplines, a quantum leap in the understanding of our planet's interior - the constitution and evolution of spaceship Earth - is about to take place if we can better understand the key issues and how to address them by fully utilizing complementary disciplinary data and modeling tools. A related goal is to try and attract more numerous talented undergraduates to consider graduate studies in geophysics.

Such a framework can best be achieved through the creation of an institute modeled after some existing examples in other fields, such as the Institute of Theoretical Physics in Santa Barbara. More closely related, is the recently created Institute for Research on the Earth Evolution (IFREE) in Japan. In contrast to the latter, which is a research institute, the proposed institute would have minimum permanent staff, and would be dedicated to providing a stimulating environment for a critical mass of visiting senior scientists, resident post-doctoral fellows and graduate students, selected at any given time to represent the various disciplines around a selected theme. The main on-going activity of the Institute would be to organize workshops and short courses on focused topics/themes of multi-disciplinary interest, not excluding disciplinary topics that might be perceived as relevant to further the collective education of the corresponding community. In addition, the institute could provide a useful framework for community activities such as, for example, the on-going development of the new Reference Earth Model (REM), a data gathering exercise, combining input from seismology combining input from seismology and mineral physics, which constitutes an incremental step towards ultimate goals that are common to those of the Institute, as clearly articulated in the REM proposal (Masters et al., 2001).

In the present proposal, we do not ask support for the Institute. That can only be defined and established through an extensive planning process, involving a wide cross section of the geoscience community. We here propose to initiate this process by holding a series of 4 workshops over a period of 1 to 2 years, whose product will be to define the scope and activities of the future Cooperative Institute for Deep Earth Research (CIDER). The name of the Institute is, at this point, by no means definitive, and, if successful, its initial focus on "deep earth" will eventually be expanded.

The proposal is submitted by PI's at UC Berkeley, who represent each of the main relevant disciplines and builds upon the multidisciplinary strength of this particular institution. We have formed a "Steering Committee" (Table I) which will be in charge, over the next two years, of organizing the workshops and refining the concept of the future Institute, with input from the community and from NSF.

Table 1: CIDER first Steering Committee Members (see letters of collaboration in Appendix)

Name	Discipline	Affiliation
M. Bukowinski	Mineral Physics	U. C. Berkeley
D. DePaolo	Geochemistry	U. C. Berkeley
A. Dziewonski (Chair)	Seismology	Harvard
G. Glatzmeier	Geodynamics	U. C. Santa Cruz
S. Hart	Geochemistry	WHOI/MIT
R. Jeanloz	Mineral Physics	U. C. Berkeley
L. Kellogg	Geodynamics	U. C. Davis
M. Manga	Geodynamics	U. C. Berkeley
G. Masters	Seismology	U.C. San Diego
P. Olson	Geodynamics	Johns Hopkins
B. Romanowicz	Seismology	U. C. Berkeley
E. Stolper	Geochemistry	Caltech
D. Weidner	Mineral Physics	SUNYSB

Note: Mark Richards (UCB, Geodynamics) will take active part in the workshops, but is not listed as a Steering Committee member because of an upcoming conflict of interest, as he will become Dean of Physical Sciences on 07/01/02.

3) SCIENCE BACKGROUND

Seismology

In the last 20 years, seismic tomography has become a powerful tool for the investigation of the deep earth, opening the possibility of 3D imaging of the earth's interior and of obtaining an accurate snapshot of the current dynamic processes.

Among others, global seismic tomography has provided constraints on some striking characteristics of the long wavelength deep structure: the distribution of heterogeneity in the topmost 200 km of the mantle correlates well with surface tectonics (slow ridges, fast shields..), but the correlation is lost at greater depths (e.g. Woodhouse and Dziewonski, 1984). Heterogeneity is strong in the uppermost mantle, decreases in the mid-mantle, where its spectrum is largely white. Inclined zones of faster than average velocity have been associated with lithospheric slabs plunging deep into the mantle (e. g. Bijwaard et al., 1998; van der Hilst et al., 1997; Fukao et al., 2001). Seismic tomography has also revealed the existence of increased, organized heterogeneity in the last few hundred kilometers of the mantle (Su et al., 1994; Masters et al., 1996; Ritsema et al., 1999; Mégnin and Romanowicz, 2000), dominated by degree 2 in the sense of a spherical harmonics expansion, and in particular the presence of two extended zones of low velocity, under the Pacific and under Africa, referred to as "superplumes", surrounded by a ring of fast velocities, which it is tempting to relate to a slab graveyard (e.g. Woodhouse and Dziewonski, 1989). On the other hand, the presence of extensive transverse isotropy in the asthenosphere under the central Pacific cannot be linked in a straightforward manner to implications from simple plate motions (Ekström and Dziewonski, 1997). Maps of the topography of the major upper mantle discontinuities have been obtained, revealing both local and large scale variations (e. g. Flanagan and Shearer, 1998a,b; Eastabrook and Kind, 1996; Gu et al., 2001). Complementary forward modeling approaches of seismic travel times and waveforms have shown that anisotropy and strong lateral gradients of structure are present in the D" region (Wysession, 1996, 1999; Russell et al., 1998; Bréger and Romanowicz, 1998; Ritsema et al., 1998) and possibly to some height above it, difficult to explain by thermal processes alone. It is also necessary to invoke some level of chemical heterogeneity, in order to explain the observed anti-correlation between lateral variations in bulk sound velocity and shear velocity in the bottom 500-1000 km of the mantle (Su and Dziewonski, 1997; Masters et al.,2000), and, if confirmed, the anti-correlation between density and shear velocity (Ishii and Tromp, 1999).

Deeper in the earth, investigation of travel times of core sensitive phases, as well as normal mode splitting measurements, have led to the discovery of inner core anisotropy (Morelli et al., 1986; Woodhouse et al., 1986), which has challenged mineral physicists and geodynamicists to provide an explanation for its origin (e.g. Jeanloz and Wenk, 1988; Karato, 1993, 1999; Stixrude and Cohen, 1995; Bergman, 1997; Steinle-Neumann et al., 2001).

Yet many controversial issues remain regarding the interpretation of seismic observations both in the mantle and in the core. Different tomographic models, obtained with seemingly similar datasets and inversion approaches, disagree on the depth extent of continental roots, with implications both for geodynamics and for geochemistry. In the transition zone and below, long wavelength S velocity models, constructed using a combination of surface waves and body waves, can be contrasted with high resolution P velocity models, constructed using mostly short period travel time data. The latter show detailed, narrow features around subduction zones, where their resolution is best, indicating that in some regions, slabs appear to flatten out at the bottom of the transition zone, while in others, they seem to be continuous across the 670 km discontinuity. The former on the other hand, exhibit generally broader fast zones, which cannot everywhere be interpreted as filtered versions of the slab related narrow fast anomalies: there are places where fast anomalies do not correspond to any known past or present subduction. These different views of the mid-mantle have implications for the fundamental convective regime, and the degree of separation of upper mantle and lower mantle geochemical reservoirs (Figure 1). The long wavelength models also show prominent low velocity columns extending vertically from the bottom of the mantle "superplumes", possibly throughout the lower mantle. Their relation to surface hotspots is intriguing, and their role in the global mantle circulation has yet to be clarified, as is the controversial issue of whether high or low densities are associated with the base of the "superplumes".

The D" region remains largely controversial. For example, the nature of the discontinuity detected at its top (Lay and Helmberger, 1983) and whether it is a global feature is still the subject of debate. Localized zones of "ultra low" P velocity, with velocity reductions in excess of 20% over several tens of kilometers, have been documented at the base of the "superplumes" (Garnero and Helmberger, 1996), but there are no systematic observations of commensurate reductions in S velocity (e.g. Castle and van der Hilst, 2000). Yet, constraining processes that take place near the core mantle boundary are essential to further our understanding of thermal and chemical exchanges between mantle and core.

Initially proposed models of inner core anisotropy were very simple, essentially constant transverse isotropy with fast axis parallel to the earth's rotation axis. As the available datasets grew, however, major complexities appeared, requiring the introduction of significant differences in the strength of anisotropy in the so-called quasi-eastern and quasi-western hemispheres as well as a possible surficial isotropic layer (Tanaka and Hamaguchi, 1997; Creager, 1999; Song and Helmberger, 1998; Garcia and Souriau, 2001). This has introduced further challenges for the geodynamic interpretations and prompted some authors to question whether the observed complexity originates in the inner core or rather, in the deep mantle (Bréger et al., 1999; 2000).

Within the next few years, the accumulation of high quality digital waveform data from a combination of sparse permanent and denser temporary broadband seismic networks, such as through the IRIS program in the US and the planned EARTHSCOPE USArray, or the Federation of Digital Seismic Networks on the international scale, signifies that advances in the field will not be limited by data, but rather by processing and interpretation methodologies. As efforts continue to incorporate accurate 3D wave propagation computations into the analysis, so that more and more information can be extracted from the observed time series, and full waveform inversions with accurate theoretical kernels can be performed owing to increased computer capacity, fundamental limitations that will remain have to do with inherent non-uniqueness of the inverse problem. This is where an integrated approach combining other disciplines relevant to deep earth studies holds tremendous promise.

While seismologists and geodynamicists have joined forces for some time to combine seismological and geodetic data in order to constrain the viscosity layering of the mantle (e.g. Hager et al., 1985; Forte et al., 1994), most global seismological studies result in maps of velocity (less frequently Q, anisotropy) distributions which are used as proxies for temperature and composition, with inherent ambiguities. Incorporation of knowledge from mineral physics about relations between elastic parameters and physical parameters more directly relevant to dynamics (temperature, composition, flow directions) would allow direct inversion for the latter, and addition of physical constraints or testing of geodynamic hypotheses. Likewise, model parametrizations have so far been designed for mathematical convenience, rather than being guided by the morphology of natural processes, which would again open the way to enlightening hypothesis testing. Constraints from geochemistry have never really been incorporated in any significant way in seismological studies, even though potential there clearly exists (e.g. the Dupal anomaly, Castillo, 1988; Hart, 1984; Dupré and Allègre, 1983), probably because substantial efforts are needed to represent the geochemical data in a manner useable in tomography and other seismological studies.

In order to make progress along these lines, seismologists must understand the capabilities and limitations of other geoscience fields much better than they do now. They must try to find a common language and the right framework for successful incorporation of various constraints. This can only happen through an intense cross-educational and dialog process, for which the appropriate environment will be provided by CIDER.

Geochemistry

The issues regarding mantle dynamics and geochemistry have recently been summarized in review papers by Van Keken et al. (2001, 2002), which update earlier reviews by (Zindler and Hart 1986; Silver et al 1988; Carlson 1995; Hofmann 1997, and DePaolo, 1988). Many aspects of the issues are also discussed by Davies and Richards (1992).

A primary issue, recognized for at least 20 years, is that geochemical evidence suggests that the modern mantle is "layered," or at least zoned, such that the uppermost mantle is more depleted in incompatible elements than the deeper parts of the mantle (eg. DePaolo and Wasserburg, 1976).

The inference of vertical stratification is based largely on the idea that the volcanism associated with passive upwelling at mid-ocean ridges provides a sampling of the shallow mantle, and the plumes that support volcanism at hot spots provide a sampling of the deep mantle. This geochemical evidence has so far been difficult to reconcile with what is currently understood about mantle convection and seismic structure. Numerical convection models do not show much indication that stratification can be preserved, or that the upper and lower mantle differ much in terms of mixing efficiency, and seismic and mineral physics data suggest that there may be no barriers to radial flow.

There has been progress over 20 years in defining the problems, but in many ways the issues facing the community now are not much different than they were in 1982 (eg. Kurz et al., 1982). Diverging approaches and viewpoints have made it almost impossible to arrive at the equivalent of a "standard model" that would reconcile at least most of the observations and be broadly accepted as a platform for further research. We see this as a clear indication of a need for an institute of the type we are proposing.

The current geochemical state of the mantle may or may not be fairly represented by the mid-ocean ridge basalt (MORB) - ocean island basalt (OIB) dichotomy. The reality of the dichotomy has been challenged (Anderson, 2001). But in any case, the apparent layering, if not an illusion, may be either a longstanding feature of the deep earth or something more like a dynamically maintained steady state feature. What can be fairly assumed is that: (a) chemically fractionated material (continental crust and oceanic crust) has been extracted from the mantle in a semi-continuous way over the entire history of the earth, leaving domains in the mantle with complementary depletions (b) continental-type material, as well as ocean floor, is currently being continuously subducted, and thus returned to the mantle (presumably) with isotopic and chemical signatures betraying its time near the earth's surface, (c) mantle plumes come from fairly deep in the mantle, if not from the bottom, (d) the largest mantle plumes carry He that looks primordial (Farley and Neroda, 1998), (e) the mantle material that melts to form MORB cannot be representative of more than a fraction of the total mantle, (f) mantle convection causes stirring of all of the components generated by partial melting and subduction ($\pm$ delamination) such that heterogeneities generated by different means can be juxtaposed as well as attenuated over time.

Attempting to make a model that accounts for these "observations and reasonable assumptions" immediately runs into many problems. For example, the current convection pattern and volcanism style and distribution may not be applicable to all of earth history (e.g. Allègre, 1997). The chemical transfer functions mantle-to-continental crust, and ocean floor-to-deep mantle are complicated because of the processes in subduction zones, a problem that has been recognized in recent efforts to focus attention on the geochemical dynamics of subduction zones by the Margins Initiative (http://www.ldeo.columbia.edu/margins/Home.html ; Subduction Factory) and its role in GERM Initiative as well (Staudigel et al., 1998). Separating the "upper" from the "lower" mantle in a way that accounts for the putative layering depends on how one estimates the mass fluxes and evaluates the physics of convection and the seismological observations (Porcelli and Wasserburg, 1995; Kellogg et al., 1999; Galer and O'Nions, 1985).

Independent of specific dynamical models for the mantle, it appears that many of the geochemical anomalies can at least be categorized (as in Zindler and Hart 1986; Hart, 1988), and in some cases the origins of the heterogeneities can be assigned (eg. White and Hofmann, 1982; Hofmann, 1997). Numerical models that are used to evaluate the persistence of heterogeneities have typically been interpreted as indicating rapid mixing (or stirring), such that large-scale heterogeneity cannot be maintained. However, little attention has been paid to the idea of maintaining large-scale differences dynamically by continuous addition or creation of certain types of heterogeneities. Variability in mixing efficiency can potentially be caused by rheological variations (Manga, 1996) and by chemical variations (DePaolo, 1997).

There are several identifiable and potentially productive avenues for further investigation. Any advance in interpretation of mantle geochemistry will come from integration of the geochemical observations with constraints that come from mineral physics, seismology and mantle convection studies. This integration has begun, but has a long way to go, and currently has no organized venue.

Possible fruitful avenues of initial investigation might include:

(a) Detailed evaluation of the inferences from He isotopes (cf. Albarède, 1998). The He isotope inferences are affected by the relative partitioning of U, Th, and He in melting processes; can these be better constrained?

(b)Most models for the mantle based on geochemistry have direct bearing on the distribution of heat producing elements, and hence on mantle convection models (eg. Van Keken et al., 2001). More attention to this aspect of the problem is needed; can models be developed that accommodate the heat production?

(c)Can large scale layering of the mantle be maintained dynamically within the context of whole mantle convection models; not just by differences in mixing properties but by differences in the production or injection of heterogeneities?

(d)Are there fractionation processes that can affect the trace element and isotope systems that are not currently accounted for; such as melting and melt segregation deep in the mantle?

(e)To what degree do we have to worry about core-mantle chemical interaction? How can this be effectively addressed?

(f)Can we develop melt generation and transport models to the point where we better understand just how volcanism samples the mantle material that is melting? Removing or quantifying the "preferential sampling" idea would help to move people closer to a common view of the implications of geochemical data (cf. Spiegelman, 1993)?

(g)Can we account for the dynamical evolution of the Earth, from the accretion-core formation-bombardment-high-temperature- low viscosity initial phase to the present? And to what degree are the difficulties we have with understanding the present state of the system due to inheritance from earlier, different dynamical regimes?

These questions are offered as a few of what perhaps is a much larger number of possible directions to investigate. What is common to all of them is that they will not be adequately addressed without an interdisciplinary approach, and only by bringing together people from the various contributing fields will we ever get to the point of knowing how to weigh the constraints coming from each field, and hopefully arrive at breakthrough ideas.

Geodynamics

Geodynamic modeling clearly plays a central role in furthering our understanding of key dynamic processes within the Earth, in that a successful model should be able to predict in a self-consistent way all the observables provided by other geoscience fields, such as the observed geoid, the distribution of anisotropy as inferred from seismology, the geographical distribution of observed geochemical isotopic anomalies, etc. More than three decades after the theory of plate tectonics was introduced, the field of geodynamics remains active and exciting. New questions continue to arise as improved seismological observations and additional geochemical data are pushing geodynamicists into developing a more sophisticated understanding of processes and observations than ever before. For example, improved seismological models of the lower mantle and D" region (e.g.,