review by Garnero, 2000; Saltzer et al., 2001) have renewed interest in determining the nature and origin of compositional heterogeneity in the mantle. What are the dynamic consequences of inferred heterogeneity on both present day observables and the past evolution of the Earth? These questions are of long standing interest, and are not significantly different (at least from a geochemical point-of-view) from the decades-old debate about whether the mantle is layered. The idea of large distinct reservoirs continues to hold appeal, though the proposed geometric form of reservoirs has moved beyond simple layers to range from highly deformed layers (e.g., Kellogg et al., 1999) to discrete "blobs" (e.g., Becker et al., 1999). The key to understanding the origins and implications of mantle heterogeneity is to be able to integrate dynamic models with seismological observations, mineral physics data, and available geophysical observations (e.g., Hager et al., 1984). Indeed our current models and debates about lower mantle dynamics are all based on constraints and observations from fields other than geodynamics.

Over the past several years it has also become possible to model in a "realistic" manner the most inaccessible region of the Earth: the core. How is the evolution and dynamics of the core coupled to that of the mantle? This coupling results in surface observations which in turn may provide unique insight not only into core dynamics and evolution, but also into mantle dynamics.

The next decade will bring rapid progress in computational geodynamics due to a combination of advances in computational technology and the implementation of more powerful and generic numerical methodologies. We thus (optimistically?) expect to make significant advances in our ability to model the dynamics of the core and to simulate virtually all processes of interest in the mantle. Computation may no longer be a primary rate-limiting step in understanding the dynamics and evolution of the Earth (and other planets). Rather, further understanding is becoming more limited by our inability to integrate and understand data and observations from other fields, such as mineral physics, geodesy, seismology, geochemistry, and Earth history. The effects of increased computational capability are already clear:

- The first generation of dynamo models have been produced, and new insight into the nature of geomagnetic reversals and the structure of core convection are coming rapidly (e.g., Glatzmeier and Roberts, 1995; Kuang and Bloxham, 1997). The coupled dynamics and evolution of the core and mantle can be considered in a quantitative way (e.g., Glatzmaier et al., 1999).
- 3D models of mantle convection are now commonly used instead of two-dimensional models (e.g., Tackley et al., 1994; Bunge et al., 1997; Zhong et al., 2000) allowing for a coupled study of the dynamics of geometrically different features such as plumes, slabs and plates.
- Complicated rheological models can be considered (e.g., Solomatov and Moresi, 2000), and plate dynamics can be crudely simulated in a dynamically self-consistent manner (e.g., Trompert and Hansen, 1998; Tackley, 2000a;2000b; Richards et al., 2001)

Moreover, it is also possible to directly incorporate information from other disciplines into geodynamics models in a manner more sophisticated than ever before. Whereas seismic and mineral physics information have been incorporated for more than two decades to obtains snapshots of the Earth's interior and dynamics (Hager and O'Connell, 1981; Forte and Mitrovica, 2001), recent studies, made possible by computational advances, have shown how plate histories can be integrated with convection models to better constrain the dynamics of the Earth's interior in space AND time (Bunge et al., 1998; Bunge, 2002).

There are certain problems that will remain computationally challenging, in particular processes that depend critically on length and time scales that are much smaller than can be resolved numerically. Examples include core dynamics (see review by Glatzmaier and Roberts, 2000) and thermochemical convection (e.g., van Keken et al., 1997). Also challenging are the processes of mixing (e.g., Ferrachat and Ricard, 2001), melting and melt migration (e.g., Spiegelman et al., 2001), processes that are critical to understand if we want to relate models to geochemical and petrological observations. In the case of both core dynamics and thermochemical convection we expect experimental studies to continue to provide insight and guidance (e.g., Sumita and Olson, 1999a; 1999b; Davaille, 1999; Jellinek et al., 2002) – and they could also provide results (e.g., entrainment of chemical species, scaling for computationally inaccessible scales) that could be incorporated in numerical simulations.

Given the expected advances in our ability to simulate and understand geodynamic processes, what is the next step in achieving the aims of geodynamics research? As we are suggesting in this proposal, we feel that the most significant advances, and hence the next step, will be to better integrate the various subdisciplines represented in this proposal to emphasize holistic process studies. By this we mean that the geodynamics, chemistry, mineral physics, and (observable) seismic properties should be viewed as outcomes of processes, rather than simply different windows or points of view.

Essential to accomplishing the hoped-for level of integration is having well-maintained tools and sufficient expertise in one place and available to all with ambition and curiosity. Geodynamicists will no longer be (or attempt to be) the "grand interpreters" of geochemistry, seismology, and mineral physics. Rather, the role of geodynamics will be to provide the expertise in imagining, modeling, and understanding mechanical processes within the Earth. Geodynamics can thus play a role in guiding the research directions and focus in other fields by providing insights into what observations and measurements will be be most useful for understanding deep Earth dynamics and evolution.

The proposed workshops and deep earth institute could play a critical role in providing an interactive setting in which geodynamicists could learn about other fields at the level necessary to pursue holistic studies. At the very least the workshops would provide an educational environment in which we can, as a community, provide collective input into new interdisplininary research directions. A more ambitious goal is to make the basic modeling tools of geodynamics (theoretical, numerical, and laboratory) useful to a broader audience of scientists in earth and planetary sciences, so that the feedback loop between observation and measurement on the one hand, and theory and modeling on the other, becomes a less disjoint and more fluid aspect of our science.

Examples of questions that are relevant for using geodynamic models to understand Earth dynamics and evolution, and that could be discussed at the Geodynamics workshop, include (only one question is listed from each of the subdisciplines that study the deep Earth):

- What advances in geodetic measurements will provide new insight into the coupled dynamics of the core and mantle?
- Can seismologists detect subvertical plumes and sloping thermochemical boundary layers in the mid-mantle? And if so, what are the limitations and uncertainties in such seismic observations? Will new seismological approaches and techniques need to be developed?
- What constraints are there on the temporal evolution of geochemical reservoirs?
- Computational models and experimental measurements of mineral properties focus on thermoelastic properties (elastic constants, thermal expansion, etc.). Geodynamic processes are most dependent on transport and rheological properties. What is the potential to determine such properties experimentally or computationally?

Mineral Physics

A key role of mineral physics is to help transform geophysical observations on the Earth's interior, notably from seismology, geodesy and geomagnetism, into an understanding of the dynamics and evolution of the planet as modeled by geodynamics and constrained by geochemistry. In this sense, mineral physics provides a link between what is observed and what we want to know, in order to understand our planet and its geological evolution.

Outstanding problems of broad importance for the geosciences include understanding the state of heat and mass transfer across the mantle and across the core-mantle boundary throughout Earth history. For example, to what degree has core composition been altered - or not - through chemical reactions with the overlying mantle, and what combined geochemical constraints (e.g., Re-Os signatures; metal-silicate electrochemistry) and geophysical consequences (distribution of heat-producing elements; influence on the geomagnetic field) can be inferred from existing data? Other questions extend to considering the extent to which the Earth's deep interior has served as a major reservoir for volatile molecules, thus influencing the geological evolution of the hydrosphere and atmosphere at the surface. In particular, what constraints are offered by seismology and mineral physics (e.g., properties of relevant phases, magnitudes of expected velocity anomalies), and what are the geodynamic (rheological) and geochemical consequences? Even at the center of our planet, the geological history of the inner core is a combined problem in seismology, geomagnetism and geodynamics that can be fruitfully addressed with the aid of mineral physics (e.g., Steinle-Neumann, et al., 2001; Buffett and Wenk, 2001).

Although the properties of Earth materials control the planet's thermal, mechanical and chemical evolution, these materials are largely hidden from direct observation. Detailed interpretations of the geophysical and geochemical data must contend with the wide range of pressure and temperature inside the Earth (360 GPa and possibly 7000 K, respectively): conditions that pose difficult challenges both for experiment and theory. Indeed, the pressures are sufficient to induce significant changes in crystal (and melt) structure, as well as in interatomic bonding (e. g., insulator-metal transitions, low spin-high spin transitions, large changes in elastic anisotropy) (Bukowinski 1994; Stixrude et al. 1998; Alfe et al. 1999, 2000; Laio et al. 2000). Attempts to understand these phenomena require developments that push the very frontiers of condensed-matter physics, yet the application of this understanding depends on close collaborations spanning the geosciences.

Both theory and experiment have experienced enormous technical advances in the past decade, with prospects of even greater strides in the coming years. The application of major accelerator facilities (synchrotron sources of x-rays and infrared radiation; neutron sources) and other laboratory methods (e.g., laser spectroscopies, high-resolution microscopies), as well as improvements in theoretical approximations (i.e., better understanding the underlying physics) and in computational power characterize this progress. Thus, it is now possible to essentially reproduce the conditions existing throughout the Earth's interior, with in-situ characterization of materials at high pressure and temperature supported by theoretical study. Elastic-wave velocities, isotopic partitioning, electromagnetic and rheological responses are among the key properties that can now be documented at deep-Earth conditions (e.g. Shim, et al. 2001).

It is these technical advances that EAR's new COMPRES initiative is intended to sustain, yet there needs to be a broader context for discussion in order to make the results most useful to the geophysical and geochemical communities. At the most technical level, a cross-disciplinary dialog is required in order to identify the key improvements in resolution and accuracy that are required among laboratory experiments and theoretical calculations in order to match those of the observations from seismology and other disciplines. Recent work shows that interpretations of the transition-zone structure and of lower-mantle properties depends to a surprising degree on details of the high pressure-temperature calibrations that are used to interpret different experiments; previous findings thought to be mutually incompatible are now turning out to be reconcilable. Mutual consistency among experiments, theory and observations pertaining to the Earth's interior – with a reliable estimate of uncertainties – is a goal that would now be in reach.

Fundamental problems requiring appropriate communication across the disciplines include the issue of scaling: how does one relate what is measured in the Earth at one scale with what is determined in the laboratory or through theory at very different scales? The interpretation of seismological heterogeneity and anisotropy is crucially dependent on addressing this issue, which then has implications for dynamical inferences about the long-term evolution of the planet. Ultimately, it is by the communities informing each other about the opportunities and limitations of available approaches that one can identify the high-value efforts that are required to advance the science.

3) THE FUTURE INSTITUTE: A PRELIMINARY OUTLINE

Although we do not explicitly request funding for the future CIDER (Cooperative Institute for Deep Earth Research) at this stage, it is useful to briefly clarify in broad terms what we have in mind. This needs to be understood as a very preliminary strawman, and none of the details must be taken as definitive.

We envision that CIDER will have minimal permanent staff, and will piggy back to some extent on existing infrastructure (at Berkeley, or possibly elsewhere). Specific to the institute will be some level of administrative assistance to handle the logistics of travel and accommodations for visitors, and support the organization of institute activities, as well as (partial?) support for a computer systems manager to administer the network of desktop computers of the Institute, and other IT infrastructure. Web managerial and other such tasks would be performed by part time student employees.

CIDER will be governed by a Director and a Steering Committee (or Board) with broad discipline/institutional representation, who will review themes and schedules for institute activities as proposed by members of the geoscience community (domestic and international), which will be widely engaged in this process.

In its steady state operational mode, CIDER would host several (4-5) post-doctoral fellows for periods of 6 to 12 months, and several graduate student fellows (4-5) for semester long internships. These would be selected to respect a balance between disciplines. Senior visiting scholars would be provided partial support towards sabbatical-type stays, and also selected to represent complementary disciplines. The Institute would hold conferences/workshops (several days) and short courses (several weeks to several months) on topics proposed by the community, attended by larger groups. These would serve different purposes, such as, among others:

- Educating the community about the status of knowledge in a specific discipline.
- Filling perceived gaps in the education of junior geoscientists (for example theory)
- Benchmarking methodologies and codes in different disciplines
- Constructing community models (e.g. provide framework for such activities as REM (http://mahi.ucsd.edu/Gabi/rem.html), or GERM (Geochemical Earth Reference Model: http://earthref.org/GERM)
- Attracting talented majors in physics/maths or other fields to geosciences.

On the latter subject, a summer session could take advantage of the University summer program, for example by offering a geoscience overview with lecturers drawn from visitors to the Institute. Several internships could be offered to undergraduates from other campuses.

4) PROPOSED WORK: FOUR PLANNING WORKSHOPS

In order to allow for the detailed planning of future courses and co-ordinated multidisciplinary research projects, we propose to start by holding a series of four conferences/workshops aimed at educating geo-scientists across their respective disciplines. All four conferences will address the question of global earth structure, evolution and dynamics, but from the point of view of a particular field, with additional lectures describing constraints imposed by other fields. The idea is that seismologists, geochemists and dynamicists would learn about the status of the field of mineral physics and what information/constraints mineral physicists expect from other fields, from Conference 1., etc. So, even though there would be some overlap, it would be minimal and it would be advantageous for anyone to attend three, and may be even all four of these meetings. These will be five day conferences, with formal lectures complemented by brief presentations, adequate time for discussion and, possibly, posters devoted to illustrating on-going multi-disciplinary research. Contrary to most workshops and research conferences, the lectures will be mostly tutorial, i.e. would not have an emphasis on the latest controversial findings in a particular research group, but rather on reviewing the well-established results and their uncertainties. The distinct difference with respect to research conferences such as Gordon or Chapman would be the emphasis on **what we do not know**, what the current limitations are in the particular field considered, and what critical multidisciplinary experiments might help in order to obtain a coherent model of the dynamics of the deep interior of the Earth. Also, the goal of each workshop will be to produce a document summarizing recommendations for activities of the future Institute. Taken together, these documents will serve as the basis for the preparation of a proposal towards the establishment of the Institute.

We suggest that the co-chairs be members of the Steering Committee, with the possibility of involving additional experts as needed. Lecturers will be chosen among recognized experts in the various disciplines. The Steering Committee will establish the general content of the lectures in consultation with the lecturers, in order to assure a balanced and as complete as possible coverage of the topics. They will constitute a workshop committee whose task is to ensure the delivery of the target product of the workshop. The workshops will be widely advertised (by e-mail lists as well as through ads. in EOS and other venues). Scientists will be encouraged to apply through a workshop announcement process, and selected within the limit of 100 participants, in order to represent a balanced distribution of disciplines. In view of the goal of the workshops, which is to refine the scope and range of activities of the proposed Institute, priority will be given to established junior and senior experts in the field. However, a number of slots (at least 20%) will be reserved for graduate students and post-doctoral fellows. These workshops will engage a community of several hundred scientists, drawn not only from the US but also internationally.

The leading themes of the conferences will be as follows:

1. Mineral physics and composition of the earth's interior (with invited talks in seismology, geochemistry and geodynamics). Chairs: (R. Jeanloz, D. Weidner, M. Bukowinski);

2. Global 3-D elastic and anelastic structure from seismology (with invited talks in geodynamics, mineral physics and geochemistry). Chairs: (A. Dziewonski, B. Romanowicz,G. Masters);

3. Constraints on composition and dynamics from geochemistry (with talks in seismology, mineral physics and geodynamics). Chairs: (D. DePaolo, S. Hart, Ed. Stolper);

4. Geodynamic models of mantle and core flow (geodynamo) with presentations from geochemistry, seismology and mineral physics. Chairs: (M. Manga, L. Kellogg, M. Richards, P. Olson, G. Glatzmeier);

Note: M. The geodynamics group is large, to allow for adequate representation of the mantle and core (in particular geomag) components.
As an example, we provide a more detailed program of Conference # 2.

Day 1: Seismological tools to investigate deep structure: capabilities and limitations

Morning: Tomographic inversion methods: Body wave travel times, surface waves and free oscillations; Forward modeling methods
Afternoon: Towards waveforms; elastic/anelastic structure; Seismic scattering as a tool in estimating stochastic properties of elastic structure; Discussion; Short contributions on Day 1 themes.

Day 2: The upper mantle

Morning: Global crustal structure; Lithosphere and asthenosphere: continental/oceanic
Afternoon: Structure of the transition zone and topography of discontinuities; Lehmann, 520 km and other proposed discontinuities; Discussion; Short contributions on Day 2 themes.

Day 3: The Deep Earth

Morning: The lower mantle and upper/lower mantle interactions; fate of the descending slabs; Structure of the mid-mantle; is it as boring as it seems to be?; Long-and short-wavelength structure at the CMB; plumes.
Afternoon: Anisotropy and the core Seismic properties of the outer and inner core; Seismic evidence for anisotropy in the Earth: crust, lithosphere, upper and lower mantle, inner core; Discussion; Short contributions on Day 3 themes.

Day 4: What seismologists always wanted to know about other fields without ever daring to ask?

- *Geochemistry*: MORB and plumes; Chemical evolution of the Earth; Evidence for and against layered mantle; General discussion; construct list of questions.
- *Mineral physics*: Mineral physics constraints on mantle composition ; Mineral physics constraints on anisotropy; Phase transformations; discontinuities (mineral physics); General discussion; construct list of questions.
- *Geodynamics*: How is convection modeled? Choice of parameters; Examples of convection models; critical assessment; What additional constraints are needed to narrow (expand) the parameter space?; general discussion; construct list of questions.

Day 5. Conclusions and Recommendations

Morning: General Discussion, construction of plan: What experiments, community projects, institute activities focused on seismology can help answer questions asked by other fields?
Panel discussion on the conclusions of Conference 2.
Afternoon: Workshop Committee: Write up conclusions and recommendations; As appropriate, plan next steps towards the Institute proposal.

The geodynamics workshop will follow the same structure as the seismology workshop. Days 1-3 will focus on the key aspects of mantle convection and core dynamics, including how these regions are studied and the current and future limitations of research on these topics. Day 4 will address key topics that geodynamicists need to understand about other disciplines. etc..

Contribution to education and human resources: This series of workshops will engage at least 20 graduate students and post-docs. Eventually, CIDER will include a graduate student and post-doc visiting program and opportunities for undergraduates to be introduced to earth sciences.