Proposal number 1100523

FESD Proposal Type II: “CIDER-II Synthesis center: Cooperative Institute for Dynamic Earth Research”

**Summary**

We propose to develop CIDER-II, (Cooperative Institute for *Dynamic* Earth Research) as a "Synthesis Center without Walls" for transformative studies of Earth's fundamental processes responsible for plate tectonics and the associated natural hazards. This requires a concerted multi-disciplinary effort of leading researchers across a broad range of Earth Science disciplines:

• Foster synergies between individuals and small groups of interdisciplinary researchers in tackling the most important and difficult unsolved problems in solid earth science;

• Provide a seed-bed to germinate ideas that will help identify the next generation of critical experiments and observations, and to build appreciation and support for them;

• Provide a venue for cross-disciplinary education of scientists at all career levels.

It has been 40 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. The indication that a transformative approach is needed and is likely to be successful comes from new interpretation of global seismic tomographic models, indicating the existence of multiple depth domains in the Earth that show different properties of heterogeneity as a function of wavelength and depth. This suggests each depth domain has its own dynamics, but with some degree of coupling among them. Generally, a much more complex problem than has been considered until now. The role of CIDER-II will be to provide mechanisms for community evaluation, validation, problem reconciliation and consensus building. In each year, the activities of this "Center without walls" will be organized around a principal multi-disciplinary theme. The kick-off for each CIDER-II "theme" will be a 6-week summer program aimed at bringing together in one place researchers across disciplines, and across career levels, to define key questions that are ripe for synthesis and/or for a concerted multi-disciplinary research effort. CIDER-II will also provide support for working groups formed to address particular practical issues identified as ripe for synthesis.

**Broader Impacts:** CIDER‘s goals are to help improve fundamental understanding of the Earth’s evolution and present dynamics through a multi-disciplinary approach. This will ultimately impact how to better address two key natural hazards issues of societal relevance: (1) natural hazards such as earthquakes and volcanic eruptions; and (2) the whole-Earth budget of volatile elements, especially water and carbon dioxide. CIDER is inherently a broad impact program: it facilitates cross-education of earth scientists at any level in their career; it aims at educating a new generation of Earth scientists with a breadth of competence across disciplines required to make progress in understanding the dynamic earth. CIDER’s web resources, including posting and webcasting of lectures given during the summer programs, as well as planned web forums and open publications, is designed to reach the entire community of earth scientists. CIDER will impact undergraduate education by producing a more broadly knowledgeable faculty cohort.

The CIDER vision was first developed almost 10 years ago. CIDER-II builds upon the accomplishments and experience gained during the CIDER-I biennial summer programs (2004-2010), which focused on the training and education of junior scientists, owing to limited resources. The goal of CIDER-II is to reinstate the original vision by providing the resources and opportunities needed to foster and conduct the necessary multi-disciplinary work.

**Project Description**

We propose to develop CIDER-II, (Cooperative Institute for *Dynamic* Earth Research) as a "Synthesis Center without Walls" for transformative studies of Earth's internal dynamics, requiring a concerted multi-disciplinary effort of leading researchers across a broad range of Earth Science disciplines. The purpose is to facilitate the work of individuals, or small groups of researchers, in contrast to a “Big Science” approach. The ultimate goal is to understand the origin, evolution, and dynamics of the Earth and planets. The practical objectives are to:

- Address the most important and difficult problems in solid earth dynamics that have defied solution thus far by fostering collaborations that can fully utilize existing knowledge and technology
- Provide a seed-bed for ideas that will identify the next generation of critical experiments and observations, and build support and appreciation for them
- Provide a venue for cross-disciplinary education of scientists at all career levels, and in particular, educate a new generation of Earth scientists with a breadth of competence across disciplines.

The notion of "Synthesis Center" can have different meanings. In the case of CIDER-II, the goal is to develop a community oriented, open facility that will identify key cross-disciplinary problems to tackle, foster the development of integrative ideas and address a broad range of cutting edge questions around the overarching general theme of "how the earth works?". The CIDER vision was first developed almost 10 years ago, when the first CIDER proposal was submitted to the NSF/EAR/CSEDI program, with, as leading motivation, the need to elucidate the driving mechanisms of plate tectonics. Owing to the reduction in scope and budget from the original request, CIDER-I's scope was necessarily restricted to student training and education. CIDER-II builds upon the accomplishments and experience gained during the CIDER-I summer programs. However, the goal of CIDER-II is to reinstate the original vision by providing the resources and opportunities needed to foster and conduct necessary follow-up work across disciplines.

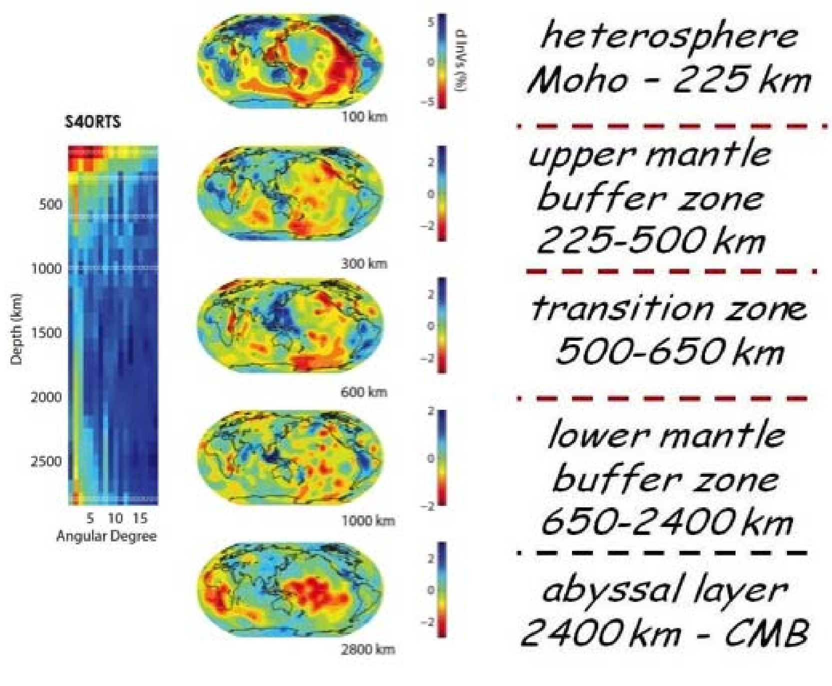


**Figure 1.** Latest published shear wave tomographic model (S40RTS, Ritsema et al., 2011). Left column: power spectrum of heterogeneity with depth; Middle column: horizontal slices at different depths in the mantle, showing the contrasted character of heterogeneity in different depth domains, labelled on the right.

## I- Eligibility Statement for FESD

***(a) Why the proposed research is poised for a major advance?***

There has been significant recent progress in interdisciplinary approaches to key global research problems. For example, geochemical tracers have been added to mantle convection simulations, and seismic tomographic models and patterns of seismic anisotropy have been used to constrain geodynamic flow models. CIDER-I has fostered the need for a new interpretation of global seismic tomographic models. These advances signify that the community is ready to move to the next level of integration, and also illustrate that the time is ripe for a Synthesis Center. Meanwhile, a new generation of disciplinary tools is becoming available that are providing unprecedented views of the Earth's interior. Given the enormous amount and diversity of observations becoming available, a significant leap in the understanding of the constitution and evolution of our planet can be expected, if we can identify and focus on the key issues that span disciplines, and build effective inter-disciplinary bridges to solve them.

***(b)Why this requires a multi-disciplinary team approach?***

Progress requires broad knowledge of multiple fields, more than any one expert can encompass. We must also fully integrate and utilize complementary disciplinary data and modeling tools (e.g. seismic wave propagation, regional geodynamics and convection simulations, *ab initio* mineral physics computations). Such integration requires better understanding of these data and tools across disciplines. Individual disciplines tend to operate in parallel, not always recognizing the need for communication across disciplines and are often hampered by the lack of a common language. CIDER-II will provide the framework to enhance these interactions.

***(c) How it addresses coupling of dynamic processes across temporal and/or spatial scales?***

The dynamics that drive plate tectonics involve the movement of mass and heat at virtually all length and time scales. Indeed, convection of the mantle and core, the dynamics of thermo-chemical plumes, movement of tectonic plates at the surface, and infiltration of magma and other fluids in the boundary layers offer dramatic examples of Earth's ongoing geological evolution.

***(d) How it goes beyond existing approaches that can be addressed within the core programs***

Conventional grants for interdisciplinary research through programs like CSEDI or even through the current solicitation do not eliminate the need for a synthesis center. We seek to create the framework for a multidisciplinary critical review of the present state of knowledge to determine what is known, what hypotheses can be eliminated and what observations and theoretical developments are required to resolve current controversies. We intend to create a domain of interaction, a sort of "incubator", where we can develop a common language and then design, plan, and initiate the collaborative research required to achieve frontier discoveries.

***(e) "High-risk, high-return" research***

The ultimate scientific goal of CIDER-II is to foster multi-disciplinary work in the community so as to achieve a clear understanding of the mechanisms that drive plate tectonics. This is a fundamental issue that has defied solution in half a century.

***(f) Creative, integrative and effective broader impact activities***

The broader impacts of CIDER include: (1) advance scientific discovery by developing and sustaining interdisciplinary networks of scientists to collaborate on grand challenge questions in the solid earth; (2) engage a diverse group of early career scientists in these research networks, training them in the diverse methodologies used by earth scientists, and mentoring graduate students and postdocs in interdisciplinary research; (3) disseminate scientific results and research-based educational material aimed at the college and graduate student level, by developing and maintaining an interactive website containing CIDER tutorial materials, and through open-access publications; (4) integrate research and education through interdisciplinary workshops and tutorials; (5) CIDER will impact undergraduate education by producing a more broadly knowledgeable faculty cohort teaching courses from the introductory level thru advanced undergraduate level.

## II- Scientific Motivation

*The need for a concerted multi-disciplinary approach*

Half a century since the acceptance of plate tectonics theory will be celebrated in five years time, the life time of the proposed program, if funded. Even though this goal has not yet been reached, the developments that took place within the activities of CIDER I make the need to establish a "synthesis center" related to Earth's dynamics even more compelling. No definitive agreement has yet been reached among geoscientists as to 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 (e.g. Lay et al., 2008); about the degree to which the mantle is chemically and/or rheologically stratified and whether there is layered or whole mantle circulation (e.g. Tackley, 2007); about the role that the cratonic roots, subduction zones, and secondary convection play in upper mantle circulation; about the conditions that favor the generation of continental crust and lithospheric mantle and the secular variation of these conditions; about the necessary rheological and compositional controls needed to generate long-lived continents; about the origin and even the existence of thermal mantle plumes rising beneath hot spot volcanic centers like Hawaii and Iceland; the chemical/thermal nature and origin of heterogeneity in the deep mantle, the nature and importance of mechanical coupling between the mantle and the core; the chemical composition of the core and its evolution; and the nature and importance of chemical exchange between the upper mantle, the deep Earth and surface reservoirs, especially of water and carbon dioxide.

The geological record provides an integrated history of our planet's mass and heat fluxes, and these lie at the heart of understanding how our planet has evolved over geological time. Geophysical observations (seismology, geodesy, geomagnetism) yield information about the current dynamics of the interior, and how these sustain the geodynamo and surface plate motions. The time scales of these internal processes can be constrained by the paleomagnetic and geochemical isotopic signatures of materials derived from the mantle (magmas, xenoliths, diamonds, etc). Petrology and mineral/rock physics provide information about the properties of Earth materials, and then geodynamical models can be used to reconcile and interpret the full range of geological, geophysical and geochemical observations.

The problems that confront solid Earth research are especially challenging, for several reasons:

- Remote-sensing of structures, processes and compositions at great depth, with no direct sampling or ground-truth, requires new theories, geophysical inference, inverse theory, and sophisticated computational modeling capabilities coupled to high performance computing.
- A wide range of pressure/temperature conditions, including the extreme conditions in the deepest interior that are difficult to reproduce in the lab setting, compositionally complex materials with multiple interacting properties operating over space- and time-scales covering many orders of magnitude (e.g. Hacker et al, 2003, Duffy, 2008).
- The intrinsic complexity of the Earth's internal systems and the constraints on our observations and laboratory capabilities push the limits of both knowledge and technology.
- Progress requires broad knowledge of multiple fields, more than any one expert can encompass.

*Why the proposed research is poised for a major advance?*

The indication that a transformative approach is needed and is likely to be successful comes from taking a new look at seismic tomographic models. Seismology can offer only a snapshot of the present state of the mantle, yet the constraints that it provides must be met by any acceptable model of the evolution of the Earth. To use this information, it is necessary to involve geodynamic modeling, the estimation of dependence of seismic velocities on temperature and composition as well as understanding of the data provided by geochemistry. As it happens, the fundamental information contained in global 3D seismic velocity models of the mantle has been available for some time, but has not been closely scrutinized by researchers in other disciplines, in particular due to the uncertainties in the models and variability of features among them. Yet, during the last two decades, a remarkable convergence among global tomographic models has developed. While the details differ, the models which are derived using data sensitive to mantle structure from Moho to the CMB show very similar features. Figure 1 shows the spectrum of lateral heterogeneity of model S40RTS (Ritsema et al., 2011) as a function of harmonic degree and depth and five maps at depths within different shells. The highest power at all depths is located at the top of the mantle, but it drops by an order of magnitude at about 200-250 km depth. For its high level of heterogeneity, the first shell is labeled "***heterosphere***". Additional research will be required to confirm properties of the second shell ("***upper mantle buffer zone***"), because of the sharp contrast with the overlying shell. The change is not only in the level of power but also in the spectral content. The map at 300 km depth shows lower velocities under oceans, but without the age signature seen in the shell above. It is interesting to note that the spectral character does not change across the 420 km discontinuity, but continues to about 500 km, below which the third shell begins, for which we use the traditional term "***transition zone***", even though its depth range is somewhat different. The main characteristic of this shell is the shift of power to a dominant degree 2, which is rather clear in the map at 600 km depth. The transition from this shell to the next (***"lower mantle buffer zone")*** involves a sharp change in the spectrum, which is weak and rather white between 650 and 2400 km depth. A map at 1200 km depth shows three anomalies that may represent "avalanches" of slabs that had ponded in the transition zone. There is no evidence for a discontinuity between the fourth and fifth shells, but there is a significant change in the radial gradient and spectrum at depths between 2300 and 2500 km; the gradient is much steeper, the heterogeneity stronger and longer wavelength in the "***abyssal layer***", which may have properties similar to those of the "hot abyssal layer" of Kellogg et al. (1999) and van der Hilst and Karason (1999), and may be related to the primordial reservoir required by some geochemical isotope studies.

The complexities described above, which occur in all models built using data sets that provide good control over structure at all depths in the mantle, indicate that a new approach to mantle dynamics may be necessary. Instead of debating whether we have "whole mantle convection" or "layered convection", we have to consider a system which shows different dynamics within different depth ranges, but with some coupling among them. Indeed, the dynamics of the heterosphere, which contains the lithospheric plates, may be affected by that of the abyssal layer (Dziewonski et al., 2010a). The high level of heterogeneity in the top 200-250 km of the mantle indicates that, to a large extent, it is self-contained, yet the lithospheric slabs penetrate to the third layer, and their descent may continue into the bottom of the mantle. The common depth at which differences between different regions of the "heterosphere" merge into one profile is inconsistent with the depth of lithosphere – asthenosphere boundary, whose depth varies with the tectonic nature of the region. Thus some other, yet to be identified process must be involved. The dominant degree 2 (and to a lesser extent degree 3) in the power spectrum of the lowermost mantle indicates little large scale mixing with a possibility that the large low shear velocity provinces (referred to as LLSVP or sometimes "super-plumes") beneath the Pacific and Africa in the "abyssal layer" may have been formed a very long time ago, yet the distribution of hot-spots at the surface and subduction zones show correlation with these deep structures.
In general, the question of the "driving mechanism of plate tectonics" cannot be addressed properly without considering the full complexity of mantle dynamics and the influence of the heat transfer from the core.

Meanwhile, a new generation of disciplinary tools is becoming available that are providing unprecedented views of the Earth's interior. Major infrastructure efforts are currently under way: Earthscope's USArray (http://www.earthscope.org) provides seismologists with a high resolution "window" into the lithosphere, deep mantle and core over the North American continent; COMPRES (http://compres.us) allows mineral physicists to perform advanced measurements on mineral properties at the high P-T conditions relevant to the Earth's deep interior, and to compare them with results of "first principles" calculations. CIG (http://www.geodynamics.org) provides geodynamicists and seismologists with a unified, state of the art framework for computations of mantle and core convection and seismic wave propagation. Extensive GPS networks and satellite observations are revolutionizing the fields of geodesy and geomagnetism (e.g. EarthScope's Plate Boundary Observatory, Oersted, Champ, GRACE and Swarm). Paleomagnetic data are being assembled into the MagIC database (earthref.org/MAGIC/). In geochemistry, the enormous volumes of high quality chemical and isotopic data gathered over the past 25 years are now part of systematic and broadly accessible databases (PETDB:www.petdb.org, GEOROC georoc.mpch-mainz.gwdg.de/georoc), and ever-improving analytical techniques are providing new perspectives on mantle processes at scales from micrometers to thousands of kilometers.

Given the enormous amount and diversity of observations becoming available, a significant leap in the understanding of the constitution and evolution of our planet can be expected, if we can identify and focus on the key issues that necessarily span across disciplines, and build effective inter-disciplinary bridges to solve them.

Although we will harvest phenomenal new observational constraints from the programs noted above, there is also a need for continuing dialogue to identify the critical data needs that will guide the next generation of field and laboratory experiments. At present there are few opportunities for developing new types of data sets, because of the expense involved for major projects and the difficulty in developing a community consensus about what data are really needed and how best to acquire them. The difficulty in targeting directions worthy of major new projects and in developing broad support for them, is a continuing, self-imposed limitation within the geoscience community.

With the increasing scope and complexity of our investigations, it is also necessary to more broadly educate the talented Earth Science graduate students attracted to our field. Indeed, it is becoming increasingly difficult to even expose them to the breadth and depth of subject matter entailed in solid Earth studies at even the largest educational institutions.

Thus, we believe that, in addition to traditional support of topical research, there is need for a sustained intellectual framework that will promote more effective cross-fertilization of the disciplines and support the corresponding education, and our experiences in the largely educational CIDER-I initiative serve to reinforce this belief. The proposed program is not meant to replace, but rather enhance and encourage the formation of small research teams that can then further develop concrete plans to address specific questions, ripe for solution within the context of a standard research proposal. For this we need a properly designed venue, where senior and junior scientists alike can thoroughly educate each other about the approaches, the fundamental achievements, the future potential and the limitations of each discipline. We seek to create the framework for a multidisciplinary critical review of the present state of knowledge to determine what is known, what hypotheses can be eliminated and what observations and theoretical developments are required to resolve current controversies. We intend to create a domain of interaction, an "incubator", where we can develop a common language and then design, plan, and initiate the collaborative research required to achieve frontier discoveries.

To some extent, Gordon Conferences on the Earth's interior, and the biennial international SEDI Conferences, provide a forum for the exchange of information and latest ideas across the different disciplines. These conferences, however, cover all possible topics in just a few days, and therefore provide only glimpses into other fields for specialists of any given discipline. Among other activities, CIDER-II will bring together, for a more extended time period (several weeks), experienced senior scientists and young minds from across all the disciplines, in an informal setting, to allow communication barriers to be broken down, questions to be formulated precisely and answered in depth. An important goal is to have several "experts" present together in a given discipline, representing different and sometimes very contrasted, or complementary, points of view on a given technical topic of interest to other disciplines. There is unique value for participants from other disciplines, and particularly the younger ones, to listen to the different points of view presented in discussion, and formulate a more objective understanding of “what is really known” versus "what is the latest ephemeral fashion" about the topic at hand, rather than base their opinion on a discussion over beer with their favorite seismologist or geochemist.

The concept of CIDER was originally put forward in 2003, based on model institutes that have existed for a long time in other fields, in particular in mathematical and physical sciences, such as the Kavli Institute of Theoretical Physics (KITP) in Santa Barbara or the Institute of Mathematics and its Applications in Minneapolis. Because existing institutes serve large communities of theorists, the model, which relies on "long programs" lasting 4-6 months, in which participants are required to spend at least 3 weeks continuously on site, needed to be adapted to the geoscience community, which has significant experimental and observational/field data gathering requirements that lead to challenging logistical issues.

Following a community workshop held at the Marconi Center, CA in May 2003, a proposal was submitted to NSF/EAR. Because of limited opportunities for funding, only the educational component of CIDER, from here-on referred to as "CIDER-I", has been developed and supported so far by the EAR/CSEDI program. CIDER-I summer programs also benefitted greatly from being hosted by KITP, who provided well adapted infrastructure support. KITP provided not only a perfect physical environment for CIDER-I, but also progressively introduced participating members of our community to the benefits of informal cross-disciplinary interactions that can develop over time frames that are longer than the typical few days of a conference or workshop.

CIDER-I necessarily focused primarily on student training and education owing to the reduction in scope and budget from the original request, and CIDER-II builds upon the accomplishments and experience gained during the CIDER-I summer programs. However, the goal of CIDER-II is to reinstate the original vision by providing the resources and opportunities needed to foster and conduct necessary work across disciplines. The scientific questions that CIDER-II will build around encompass 4 out of 6 significant research problems (research on earth and planetary materials; investigation of 3 dimensional structure and composition of the continents; studies of the earth's deep interior; planetary science using extra-terrestrial materials ( BROES Report, 2001), and all major questions regarding the earth's interior identified in the most recent NRC report (De Paolo et al., 2008). In what follows we describe the proposed activities of CIDER-II. Its organizational structure and management plan are provided as supplementary material. Accomplishments of CIDER-I are described at the end of the proposal.

**Proposed activities and organization**

CIDER-II will be constructed as a "Center without walls". In each year, the activities of the Center will be organized around a specific theme, defined with input from the community, requiring multi-disciplinary efforts. The goals of these activities will be :(1) to determine the current state of knowledge on that theme across the different disciplines, contrasting different points of view; (2) to identify the key practical next steps for research; (3) to identify suitable tasks for working groups to advance progress on this theme and initiate the formation of such working groups (4) to foster connections between individual researchers in different disciplines that will lead to the development of focused research proposals and/or publications; (5) to provide cross-education for researchers in the different disciplines and in particular engage aspiring researchers at the advanced graduate student and post-doc levels. The multi-disciplinary themes will be suggested by community members, prioritized by the CIDER Advisory Committee (AC), and implemented by the Executive Committee (EC) in such as way as to maintain a balance between themes focused primarily on the deeper earth, the upper boundary layer, and integrative themes across multiple lateral and depth scales. Examples of possible themes are given in the next section.

The role of CIDER-II will be to provide mechanisms for community evaluation, validation, problem reconciliation and consensus building. The process will include a strong web-based interactive component: posting of relevant papers and data, and on-line forums for the research group activities. In particular, we propose to develop a dynamic series of peer-reviewed synthesis articles, presenting opposing views, when appropriate, on timely topics relevant to CIDER-II, to be published on-line. More generally, significant effort will be put into developing a CIDER-II web portal, to provide electronically accessible, creatively designed products of CIDER'II's synthesis and educational activities, making use of state-of-the art web tools. Our community has so far been working primarily with traditional publication methods, but examples could be drawn from other science communities that are further ahead (Maths, Physics).

CIDER-II will provide support for working groups formed to address particular practical issues identified as ripe for synthesis (3-4 working groups per year, 10-12 members each). This support will range from IT support for organizing materials and debates, travel support for occasional working group face to face meetings, phone conferences, use of visualization tools and interfaces with infrastructure programs as well as, when appropriate, partial support for post-docs or graduate students to perform specific research tasks that are outside or beyond the work supported at their own institution. While the activities of a particular working group may result in other products, a key goal will be the development of an evolving e-based synthesis document on each topic, a sort of "wiki", or "e-book", providing a critical comparison of relevant hypotheses, with the possibility for posting "pros" and "cons" by the community. We expect that many, but not necessarily all, working groups will be initiated during the yearly CIDER Summer program. In what follows we describe in more details what the summer program entails as well as other year-round sustained activities.

*Summer Programs: initiation of the theme of the year*

Indeed, we envisage that the kick-off for each CIDER-II "theme" will be a yearly 6-week summer program aimed at bringing together in one place researchers across disciplines, and across career levels, to define key questions that are ripe for synthesis and/or for a concerted multi-disciplinary research effort. Participants in the summer program will be required to spend a minimum of 2 weeks on site. The length of the summer program is based on the experience gained in CIDER-I and the constraints (field work, experimental labs) specific to our geoscience community. Note however, that the proposed activities reach well beyond the scope of the CIDER-I summer programs, which have been focused primarily on the educational aspect (see corresponding section below).

We will maintain this successful educational component as the "core" of the summer program. It is an effective way to bring in the next generation of geoscientists early on into the CIDER integrative process. Thus, imbedded in the summer program will be a 2 week structured lecture/tutorial part aimed at advanced graduate students and post-docs, representing a balance of expertise among disciplines, which will build upon experience gained over 4 biennial CIDER-I summer programs. More senior members of the community are also encouraged to participate, not necessarily as instructors. The tutorial program aims at providing a fundamental level of understanding in all disciplines, and presentation of key challenges and state-of-the art tools in each field. In particular, it includes introductions to the use of databases and codes provided through the numerous infrastructure programs mentioned in the previous section. During the tutorial program, time will be set aside to discuss emerging science questions, relevant to the CIDER theme, that require contributions from different fields. Participants will prioritize these questions. Through an iterative discussion process, these questions will be narrowed down to 4-5 ones that "attract" a group of participants that is balanced in terms of disciplines and includes at least one senior researcher (minimum asst prof. level). The tutorial program will be followed by 2 weeks of "workshop" in which the groups thus formed will conduct preliminary work on the topic chosen. Such a process has previously been tested in CIDER-I. What will be new, is the level of support that can be provided for follow-up work.

The educational program will be embedded within an unstructured part, aimed at scientists at any level of their careers and lasting throughout the 6 weeks of the summer program. Participating scientists get a desk and access to the computer network and printers and can spend their time whichever way they like. Occasional research seminars (except during the tutorial session) provide a glue that can stimulate informal interactions. Some groups of scientists with a specific science question in mind may be formed in advance of the summer program, and use the summer program venue to formulate plans for future research or initiate working groups. Other candidate topics for working groups may be identified as a result of the informal and structured interactions. The summer program will thus provide the seed for the following year's debates and consensus building process on several key and timely topics related to the main theme. It is anticipated that the lifespan of each working group may extend beyond one year and that the corresponding electronic "synthesis chapters" will continue accruing material. Broader community workshops will be held in years 2 and 4 to review progress made and solicit input for future themes and activities.  In alternate years, the summer program will be hosted at UC Berkeley, but other possibilities are being explored (in particular, if funded, the 2012 summer program will be held at KITP, Santa Barbara).

One challenge for the summer programs, realized in Phase I of CIDER, is that it is difficult for some members of our community, in particular those that are raising young children, to spend 2 weeks or more away from home during the summer. In fact, we have addressed this on a case by case basis in previous summer programs, by providing appropriate housing for participants with families, and intend to continue doing so, by setting aside additional support for participants for this purpose.

As in previous years, the summer programs will be widely advertised on community list-servers (IRIS, COMPRES, SEDI, AGU), in EOS, and by word of mouth, and an application website will be set up. In order to qualify for support, participants must commit to stay long enough (2 weeks minimum) and demonstrate that their expertise and research interests match the goals of the summer program. Lecturers will be recruited to ensure an appropriate balance of disciplinary expertise and seniority, and will comprise a mix of returning previous CIDER lecturers (we have found that many are happy to do it again) and of first timers, according to the needs of the particular program. Students and post-docs apply to the program and are selected according to their seniority (in principle, they must have passed qualifying exams), the recommendation of their advisors, their research interests, and with the goal of achieving a balance of disciplinary expertise among them. The organizing team of the summer program makes the final decisions on all admissions.

*Sustained Activities*

CIDER-II will  facilitate support two main activities throughout the year:

(1) *activities of research teams formed during the summer programs*,
to allow full development of new research directions. This can be accomplished by providing support for follow-up work on summer program products or activities through a mechanism of research stipends to allow a graduate student or post-doc selected from each summer program team to spend up to 2 months at a collaborating institution. These stipends would be awarded after review of mini-proposals by the CIDER Science advisory committee and managed through the CIDER office. A mini version of such an experiment (modest support for groups for travel and publications) was initiated following the 2010 Summer program: while it is too early to gage final products, we note that the research teams have made presentations at the Fall'2010 AGU (Dziewonski et al., 2010b; McDonough et al., 2010; Hernlund et al., 2010; Becker et al, 2010).

(2) *Support ad-hoc working to address key topics relevant to CIDER goals,*
In addition to theme specific working groups, we envisage working groups formed, for example, tp develop consensus reports on pressure standards, comparison of aspherical seismic model predictions, comparison of deep structure seismic imaging results, production of a priori mineral-physics based elasticity models, development of a new 3D Earth model, assessment of Chondritic Earth Model framework, etc. This could be transformative for our research; there is currently no mechanism for community evaluation, validation, problem reconciliation, or consensus building. It would be a major new activity in Earth Sciences. These activities would be coordinated with other relevant communities (CIG, Compress, IRIS. Earthscope etc).
*(3) Support virtual center activities through the CIDER website*
This would include the development of the electronic book as described above, web support for communications and archiving of materials of research teams and working groups, management of on-line debate forums on the web on controversial topics of interest to the solid earth community. The forum could be similar to reading seminars (i.e., read one or two papers before the forum and invite the relevant authors to participate).

Possible themes for CIDER-II

Several themes for CIDER-II programs were proposed at the 2009 CIDER Community Workshop (Marconi Center, CA). From those, a summer program theme on "Mountain Building and Orogenesis" will be held at UC Berkeley in summer 2011 with existing funds from EAR/CSEDI. We do not describe it here, but information is available at http://www.deep-earth.org/2011/summer11.html. Likewise, the theme, "Deep Time: how did the early Earth become our modern world?" has already been agreed upon for Year 1, should this proposal be funded, and KITP will host the corresponding 2012 summer program. Marc Hirschmann (U. Minn.) has agreed to be the lead organizer of this summer program.

Note that the proposed synthesis activities related to each theme are beyond the scope of the past and upcoming summer programs, which have been focused primarily on the lecture/tutorial aspect. Each theme is meant to provide a framework to bring together the appropriate mix of multi-disciplinary researchers. The summer programs will serve to define concrete steps that can be taken to further develop aspects of the theme that are ripe for multi-disciplinary synthesis. In what follows we describe in more detail two of the proposed themes. Theme 2 is proposed tentatively, based on input from the 2009 Marconi Workshop. In practice, themes for Yrs 2-4 will be developed dynamically, with input from the community.

***Theme 1 - Deep Time: how did the early Earth become our modern world?***

Many key Earth science processes occurred early in Earth's history. The violent events of accretion determined the composition of the planet as well as its initial thermal state. The conditions of core formation determined its composition and consequently the dynamics of thermochemical convection in the modern outer core. Convection in the early mantle led eventually to plate tectonics. Early formation and recycling of crust and volatiles led to the birth of continental crust and development of earth's unique atmosphere and equable climate. A major theme of a Deep Time CIDER program will be exploring the connections between the modern and early Earth. One of the key problems is the influence of early Earth processes on the ensuing chemical and physical dynamics of the planet, including geochemical differentiation, the genesis of plate tectonics and the conditions leading to planetary habitability.

The composition, energetics, and earliest differentiation of the Earth are intimately linked with the process of accretion and the history of large to giant impacts on the growing protoplanet (Figure 2). Improvements in modeling have provided a wealth of data on accretion and impact processes, including the time scales of planetary accretion (Chambers, 2004), the delivery of volatiles to Earth from the outer solar system (Morbidelli et al. 2000; Raymond et al. 2007), as well as the consequences of a giant impact on the formation of the Moon, the creation of a magma ocean (Canup, 2004) and on the retention of $H_2O$ and other volatiles (Genda and Abe, 2005). Recent developments in geochemistry have given us greater insight into the early Earth. Evidence from $^{142}$Nd isotopes seem to require either that the Earth accreted from materials distinct from chondrites or that there is a considerable hidden geochemical reservoir deep in the Earth (Boyet and Carlson, 2005). Combination of short-lived chronometers such as $^{182}$Hf/$^{182}$W with more conventional isotopic systems sheds light on the timing of planetary accretion and its earliest differentiation, including core formation (Wood and Halliday, 2005).

Seismic tomography gives us a snapshot of contemporary heterogeneity in the mantle, but the variable pattern it reveals as a function of depth tells us much about the history and dynamics of the mantle flow. Figure 1 demonstrates that mantle consists of five layers with distinct characteristics. In particular, the "abyssal layer" shows strong concentration (50%) of spectral power in a single harmonic coefficient. This well-organized heterogeneity is unlikely to have arisen recently, as stirring should distribute rather than concentrate the spectral distribution of heterogeneities. Thus a structure such as that depicted in Figure 1 is clearly long-lived and arguably very ancient. A challenge for theories of the early Earth includes identifying processes that can account for the unique structure of the abyssal layer. In addition, seismic evidence for sharp LLSVP boundaries suggests compositional and/or rheological heterogeneity which may relate to the proposed hidden geochemical reservoirs (e.g. Kellogg et al., 1999; Tolstikhin and Hofmann, 2005). Thus, information from tomography should be used to test various hypotheses regarding the early Earth.

Further development of isotopic and geophysical probes, as well as mineral physics and geodynamical studies are required to fully comprehend how the legacy of early Earth is expressed in the deepest parts of the mantle, and determine how mantle dynamics made the transition from an early regime resulting from the solidification of magma ocean(s) to plate tectonics. For example, magma ocean solidification may have lead to density stratification of the solidified mantle (Elkins-Tanton, 2008), which in turn would have affected the style of early convection and, today, may be reflected in the partial stratification observed in seismic tomography (Figure 1). Finally, magma ocean degassing fundamentally modified the atmosphere and hydrosphere. How did early exchange of volatiles between the mantle and exosphere lead to establishment of Earth's unique atmosphere and climate?

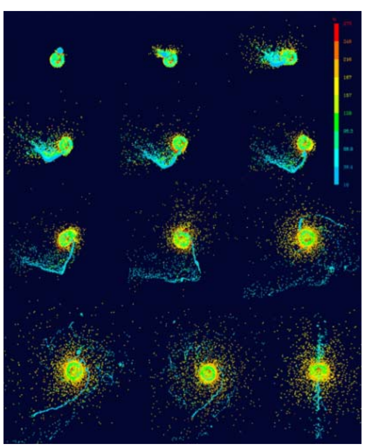

**Fig. 2.** Simulation of a giant impact between a Mars-sized body and the proto-Earth, showing the heating of the Earth as well as the creation of a debris disk leading to the formation of the Moon (Canup, 2004).

Another key aspect of Deep Time is the thermal evolution of the planet The secular cooling of Earth's interior has influenced the core, as the origin of the inner core and the powering of the geodynamo are intimately related to the history of heat fluxes across the core-mantle boundary (Lay et al. 2008). To understand Earth's thermal history, we can look at everything from the history of Earth's magnetic field, as it may record the thermal evolution of the core, to temperature dependences of the physical and chemical properties of mantle materials, to the compositions of mantle and volcanic rocks. Ultimately, we need to explain the relation of the seismic structures obtained today in the deepest mantle to those in the transition zone and uppermost mantle.

Finally, there is the question of the earliest formation of continental crust and lithosphere. Continental cratons preserve rocks as old as 4 Ga or perhaps older, but the Jack Hills zircons demonstrate that differentiated rocks not too different from modern continental crust was forming as early as 4.4 Ga (Wilde et al. 2001). Formation of this very early crust seems to have occurred along surprisingly cool geotherms (Hopkins et al. 2008), suggesting either initiation of subduction-like processes or formation of significant thicknesses of lithosphere almost from the outset of Earth history. Either possibility presents strong challenges to our understanding of early geodynamics., which need to be reconciled with present day constraints from seismology on the thickness of lithosphere and layering in cratons, the parts of the continents underlying archean crust (e.g. Yuan and Romanowicz, 2010a)

All of these topics are fundamentally multidisciplinary. Geochemistry and geodynamics play a central role in virtually all of the subjects that will be addressed, but mineral physics also provides critical information on key topics, including the chemistry of core fluids, chemical and physical properties solids and liquids in deep magma oceans, the chemical and physical properties of materials in the deep mantle, Seismology plays an important role in that it provides the principal constraints on the structure, composition, and heterogeneity of the Earth's interior, which are among the most important testable observations for models of the Earth's early evolution. Importantly, a Deep Time CIDER will also have a component of petrology, as the evidence from the rock record is a critical dimension.

***Proposed Theme 2- Origin and evolution of continents and cratons***

Unlike oceanic lithosphere, which subducts, continental lithosphere has a much longer residence time at the Earth's surface even though it is underlain by a colder and thicker (100-250 km) thermal boundary layer (Jordan, 1988). The crust in the oldest parts of continents (cratons), has remained intact for over two-thirds of Earth's history. Any recycling of continental material back into the mantle probably involves erosion of the upper crust and sedimentary transport to oceanic lithosphere (indirect subduction) or thinning of the deep crust and lithospheric mantle by subduction, erosion or small-scale convective instabilities. In this regard, continents are not mobile lids in the plate tectonic sense, but are better described as stagnant thermal boundary layers that passively drift over the Earth's surface. Continental lithosphere may be local analogs for the presumed stagnant lids of Venus and Mars. Continents play a key role in the thermal and dynamic evolution of a planet because vertical heat flow through a non-subducting lithosphere is dominated by conduction and hence inefficient (Lenardic et al., 2005). In addition, the thin (~35 km) veneer of continental crust making up the top layer of continental lithosphere houses half or more of the Earth's most incompatible trace elements, including the heat-producing elements (e.g. Hoffman, 1988; Rudnick and Gao, 2003). Finally, because of their old ages, continents hold a valuable record of Earth's history. There is thus a need to better understand how continents form and evolve. Key variables are the formation times of the continent and its various components, the thickness of the continental lithosphere, compositional structure of the crust and lithospheric mantle, thermal state of the lithosphere, rheologic structure, and the physical and chemical nature of the base of continental thermal boundary layers. While there are already constraints on many of these variables, recent advances in geochemistry/petrology and geophysics (in particular, seismology and geodynamics) have given rise to new and sometimes surprising observations or concepts that have not yet been incorporated into an updated synthesis of continent origins.

It has long been thought that cratonic mantle extends down to depths in excess of 300 km based on seismic tomography studies (cf. Ritsema et al., 2000), but this was inconsistent with petrologic constraints from xenoliths and models based on surface heat flow (Rudnick et al., 1998). More recent tomography studies focused on shear-wave anisotropy suggest that cratonic lithosphere is at most 200-250 km, consistent with the xenolith data (Gung et al., 2003). Recent seismological results from receiver function studies and anisotropic tomography indicate the presence of layering in the continental lithosphere (e.g. Rychert and Shearer, 2009; Yuan and Romanowicz, 2010). On the other hand, there is growing evidence that continental lithospheres are chemically modified by the passage of melts or fluids (Foley, 2008). Such processes could modify the seismic and dynamic structure of the lithosphere, but so far, the consequences of these processes have not been fully explored. There is also considerable controversy over how thick continental lithospheres are built. One view is that continental lithospheric mantle is the melting residue of large plume heads (Arndt et al., 2009), in which case no obvious internal discontinuities are predicted. An alternative view is that continental lithosphere is the product of numerous thickening and underthrusting events, in which case, internal discontinuities might be the norm. The fine structure of the continental lithosphere bears first-order ramifications for understanding the petrogenetic, dynamic and thermal evolution of continents.

Importantly, there must be specific reason why the power of heterogeneity suddenly drops by one order of magnitude at 250 ± 50 km. For example the water content may suddenly decrease, leading to different rheology. It will be important to determine the degree to which the heterosphere material mixes with that of the deeper shells. Figure 1 demonstrates that it is not as simple as whole mantle convection suggests.

Other examples of themes that have been proposed and lend themselves to consideration for CIDER-II, are: "Large igneous provinces, their origins and impacts"; "Flow in the Deep Earth", "Solid earth and climate", "Core structure and dynamics", "Dynamics of planetary interiors". These are given for purpose of illustration, but will require further development to assess their suitability for the pu

*CIDER-II versus standard research proposals.*

CIDER-II is not meant a substitute for traditional CSEDI or Geophysics research proposals, on the contrary, it is a complementary component of the research process. We view as one of its main goals an effective way of bringing together the intellectual resources in our community to more clearly define the questions that are ripe for focused research by small groups of PI's, their graduate students and post-docs, and that can, for instance, develop into an NSF proposal. Because of its open, community inclusive operational mode, CIDER-II will help formulate the right questions at the right time, and help assemble the right mix of competences across the disciplines and in particular, multi-disciplinary teams that may not have had an opportunity to form otherwise.

**CIDER-I Accomplishments**

The four CIDER summer programs (2004-2010) all took place at the Kavli Institute of Theoretical Physics (KITP) in Santa Barbara. The KITP site, with its office space for participants, auditorium and seminar rooms, access to computer workstations, internet, printers, and general logistical support, including video taping of lectures and seminars, provided a unique environment for CIDER-I (supported by KITP), and, importantly, it stimulated interactions between the deep earth Geoscience community and the Physics community. Table 1 summarizes the activities of CIDER Phase I, and Table 2 lists the instructors who volunteered their time for lectures and tutorials in the four summer programs.

Each summer program was attended by ~35 advanced graduate students and post-docs and 20-35 junior/senior scientists, including 4-6 international participants, who paid for their own travel. The students and post-docs were selected through an application process according to their interests and level (preferably post qualifying exam) and representing a balance of disciplines. The programs comprised 2 weeks of morning lectures, designed to provide the basic critical technical background on the tools and state of knowledge in each of the main disciplines in deep earth research, keeping in mind the specific theme of the summer program. Hands-on tutorials were given each afternoon, designed to familiarize non-specialists with practical aspects of problem solving in each discipline. This 2 week lecture/tutorial period was followed by 1-2 weeks of “workshop”, in which a number of small (5-10 people) multidisciplinary groups were formed to investigate a research topic of their choice (that had emerged during discussions in the first part of the program). Progress in the work of each group was presented in a plenary session at the end of the workshop. More specifics on these summer programs, including the PowerPoint lectures and other presentations, can be found at: http://www.deep-earth.org/index.html,. Student evaluations of the program can also be found on this website. All lectures were video-taped and posted on the KITP website: http://www.kitp.ucsb.edu/activities/past/.

In 2008, the program lasted 7 weeks. The goal was to experiment one step further with the concept of bringing together researchers young and old to interact informally over extended periods of time around a specific interdisciplinary theme. Thus, the first part of the summer program (3 weeks) was organized in true “KITP mode": participants engaged in informal interactions around the central theme of the program, with at most one formal plenary research presentation each day. This part of the program overlapped with two other KITP programs: “Dynamos” and “The Physics of Climate”. In 2010, the program lasted 6 weeks, and overlapped with a KITP program on "The Physics of Glasses". It was followed by the 12th International SEDI Symposium, also held in Santa Barbara, and organized by CIDER PI 's. Many CIDER students stayed on for the SEDI Symposium. Their feedback indicates that the CIDER experience helped them appreciate better the presentations and discussions during the conference.

In all, the 4 CIDER summer programs brought together 134 graduate students and post-docs, and 106 participants with seniority of assistant professor or higher (of which 31 volunteered as lecturers, Table 2). Two community workshops were also supported by these grants, one at the beginning, in 2003, which laid out the goals of CIDER and the other one in 2009, to review the accomplishments so far and develop a vision for the next five years (CIDER-II). The 2009 workshop brought together 83 participants, more than half of whom were new to CIDER. The workshop featured keynote presentations on 5 major interdisciplinary themes (including the 4 themes of the past and pending CIDER summer programs). The presentation ppt’s are available on the CIDER website. Former students were invited to make short presentations on their experience at CIDER and make recommendations for future programs. Particularly inspiring were testimonies of students who have now advanced in their careers, explaining how important the CIDER experience was for them on four counts: CIDER (1) broadened their education in earth science disciplines other than their own; (2) provided tutorial materials that helped them in developing courses, (3) provided an opportunity to network with their peers from other disciplines and institutions, allowing them to develop research collaborations as they are launching their careers, and (4) gave them a venue to interact with senior members of the community in a unique, relaxed environment, which subsequently helped in obtaining post-doctoral or faculty positions. Indeed, one of the tangible important impacts of CIDER has been that a significant number of CIDER-I students have subsequently gone on to faculty positions (e.g. Table 3). Other tangible impacts have been:

(1) presentations at AGU meetings (e.g. Moore et al., 2004; Reif et al, 2004; Dziewonski et al., 2006; Escalante et al., 2006; Harris et al., 2006; Lee et al., 2006; Lekic et al., 2006; Arevalo et al., 2008; Cormier, 2008; Hernlund et al., 2008; Konter et al., 2009; Becker et al., 2010; Chen, 2010; Dziewonski et al., 2010b; Hernlund et al, 2010; McDonough et al., 2010) and other conferences (e.g. Dasgupta, 2009; Roberts et al., 2009).

(2) publications that resulted from work started at CIDER or inspired by discussions and connections made at CIDER(see reference section, publications and oral presentations indicated by a "•"). Not all publications explicitely acknowledge CIDER-I, unfortunately, however, the authors have come forward to recognize the role one or the other of the summer programs had in their production.

(3) Organization of multi-disciplinary Fall AGU sessions. Among them:. , Fall AGU Meeting 2007: Warren, Lee, Cooper and Blondes: "Origin and Evolution of Continents: Lithospheric and Asthenospheric Perspectives", Romanowicz, Kellogg, DePaolo: "Whole or Layered Mantle convection?"; Fall Agu Meeting 2010: Hernlund and Kavner, " Melt-Solid Density Inversions in the Earth and Planetary Interiors II"; not to mention the entire 2010 SEDI symposium- held in Santa Barbara in conjunction with CIDER( http://www.deep-earth.org/2010/sedi2010.html)

(4) Development of research proposals to the CSEDI program. Funded proposals include: Hart and Lithgow-Bertelloni NSF-EAR-0551991**,** Manga and Hernlund, NSF EAR 0855737 " CSEDI: Melt stability and dynamics in the deep Earth";

***Selected Scientific Highlights of past CIDER-I summer programs:*** Reports of multidisciplinary groups during past CIDER-I summer programs are available on the CIDER webpage. A highlight of the 4 week 2004 Summer Program has been the opportunity to discuss and form multi-disciplinary collaborations at the time of the discovery of the post-perovskite transition in the lowermost mantle. A multi-disciplinary group thus formed and reported on their CIDER activities at the end of the summer program (see: http://www.deep-earth.org/workshop04br.html). Several publications resulted directly from this (e.g. Lay et al., 2005; Matyska and Yuen, 2005). A highlight of the 3 week 2006 Summer Program was the first effort to compare determinations of mantle temperature from petrology and seismology (see http://www.deep-earth.org/2006/workshop.html, group C) which was applied to the problem of excess temperatures in hot spots (Courtier et al., 2007). Another highlight was collaboration between seismologists and mineral physicists to consider a mineralogical model of the upper mantle based on a "mechanical mixture" rather than thermodynamic equilibrium, to try to reconcile seismic velocity gradients in the transition zone with those predicted from a pyrolite model, which inspired several publications (e.g. Cammarano and Romanowicz, 2007; Xu et al, 2008). A highlight of the 2008 summer program (http://www.deep-earth.org/2008/workshop.html) was a multidisciplinary discussion group focus on the interpretation of seismic LLSVP's, which inspired a subsequent publication calling attention to the remarkable degree 2 structure at the base of the mantle, and its likely longevity (Dziewonski et al., 2010a). Work started during the 2010 Summer program is still in progress. Five interdisciplinary groups have formed to investigate: 1) the construction of a 3D reference seismological model of the mantle (Dziewonski et al., 2010b); 2) an investigation of the interactions between the deep water cycle and the history of mantle convection (Becker et al., 2010); 3) an investigation of the possible origin of the zone of reduced P velocity gradient (F-layer) at the top of the inner core (Hernlund et al., 2010); 4) an investigation of the possible stratification at the top of the outer core (McDonough et al., 2010); 5) investigation of mantle melting in subduction zone wedges (see also the reports at http://www.deep-earth.org/2010/workshop10.html). The list of Steering Committee members that shepherded CIDER-I can be found at http://www.deep-earth.org/steering.html) .

**Broader Impacts are described in the "Eligibility for FESD" section.** Student mentoring is a core activity of CIDER through the involvement of the graduate students in the summer programs and follow-up activities

**Table 3: Former CIDER students/post-docs currently holding faculty positions**

| **Name** | **CIDER year** | **Current institution** | **Name** | **year** | **Current institution** |
|---|---|---|---|---|---|
| James Conder | 2004 | S. Illinois U. | Matt Jackson | 2006 | Boston U. |
| Ana Ferreira | 2004 | U. of East Anglia | Jessie Lawrence | 2006 | Stanford U. |
| Miaki Ishii | 2004 | Harvard U. | Gaspar Monsalve | 2006 | U. Nacional, Columbia |
| Jasper Konter | 2004 | U. Texas El Paso | Tai Lin Tseng | 2006 | Taiwan Nat. U. |
| Kanani Lee | 2004 | Yale U. | Zhengrong Wang | 2006 | Yale U. |
| Wendy Mao | 2004 | Stanford U. | Jessica Warren | 2006 | Stanford U. |
| Meredith Nettles | 2004 | Columbia U. | Tobias Hoink | 2008 | U. of Munich |
| Anat Shahar | 2004 | Carnegie | Christian Huber | 2008 | Georgia Tech. |
| Anna Courtier | 2006 | James Madison U. | Meghan Miller | 2008 | U. S. California |
| Colleen Dalton | 2006 | Boston U. | Victor Tsai | 2008 | Caltech |
| Rajdeep Dasgupta | 2006 | Rice U. | | | |

## Table 1: Chronology of CIDER-I activities

**CIDER Community Workshop: 05/24-29/03**
**Marconi Center**
77 participants from 43 institutions
Goals: Define the scope and format of CIDER

**2004 Summer Program: 07/12/04-08/06/04**
*"Relating seismological and geochemical heterogeneity in the earth's mantle"*
2 weeks tutorial + 2 weeks workshop
30 grad students/post-docs
21 junior/senior scientists

**2006 Summer Program: 07/16/06-08/06/06**
*"The earth's transition zone"*
Overlapping 2 weeks tutorial/2 weeks workshop
35 grad students/postdocs;
20 junior/senior scientists

**2008 Summer Program: 06/23/08-08/05/08**
*"Boundary Layers in the Earth"*
3 weeks KITP style (overlap with "Dynamos" + 2 weeks tutorial + 2 weeks workshop (incl. VLAB)
35 graduate students/post-docs
35 junior/senior scientists

**CIDER Community Workshop: 05/17-20/09**
83 participants from 37 institutions
Goals: review accomplishments and scope of CIDER

**2010 Summer Program: 06/12/10-07/18/10**
*"Fluids and volatiles in the Earth's mantle and core"*
2 weeks KITP style (overlap with "Physics of Glasses") + 2 weeks tutorial + 1 week workshops
35 graduate students/postdocs
30 junior/senior scientists
->Followed by SEDI international Symposium
->Follow up research activities

## Table II - Instructors in CIDER-I summer programs

| Instructor | Field | '04 | '06 | '08 | '10 | | | '04 | '06 | '08 | '10 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T. Becker<br>**USC** | **Geo-dyn** | | | x | x | T. Duffy<br>Princeton | **Min. Phys.** | | x | | |
| B. Buffett<br>**UC Berkeley** | " | x | x | x | | M. Hirschmann<br>U.. Minn. | " | | x | | x |
| S. Hier-Majumder<br>**U. Maryland** | " | | | | x | A. Kavner<br>UCLA | " | x | | x | x |
| L. Kellogg<br>**UC Davis** | " | x | x | x | | J. Li<br>**UIUC/U Mich** | " | | | x | x |
| C. Lithgow-Bertelloni U. Mich. | " | x | x | | | R. Liebermann<br>SUNY-SB | " | | | x | |
| M. Manga<br>UC Berkeley | " | | | x | x | Jan Matas<br>ENS Lyon | " | | | | x |
| P. van Keken<br>U. MIchigan | " | | x | x | x | W. Panero*<br>Ohio State U | " | | | | x |
| M. Spiegelman<br>Columbia U. | " | | | | x | L. Stixrude<br>U. Mich. | " | x | x | | |
| D. DePaolo<br>UC Berkeley | **Geo-chem** | x | | | | C. Dalton*<br>Boston U. | **Seism o.** | | | | x |
| J. Eiler<br>Caltech | " | | x | | | A. Dziewonski<br>Harvard U. | " | x | x | x | |
| S. Hart<br>WHOI | " | x | x | x | | A. Levander<br>Rice U. | " | | x | x | x |
| CT Lee<br>Rice U. | " | | x | x | x | G. Masters<br>UCSD | " | x | x | x | x |
| W.McDonough<br>U. Maryland | " | | | | x | B. Romanowicz<br>UC Berkeley | " | x | x | x | x |
| S. Mukhopadh-yay,<br>Harvard | " | | x | x | x | P. Shearer<br>UCSD | " | | | | x |
| T. Plank<br>Columbia U. | " | | | | x | A. Sheehan<br>Colorado | " | | | x | |
| *** previous CIDER student** | | | | | | J. Tromp<br>Caltech/Princeton<br>on<br>Catl | " | | | x | x |

**Publications that benefited from CIDER summer programs**


- Billen, M. I. (2008) *Modeling the Dynamics of Subducting Slabs*, Annual Reviews of Earth and Planetary Science (online access), 36, 325-356, doi:10.1146/annurev.earth36.031207.124129.
- Cammarano, F. and B. Romanowicz (2007) Insights into the nature of the transition zone from physically constrained inversion of long period seismic data, Proc. Nat. Acad. Sci., doi 10.1073/pnas.0608075104.
- Chen, W. P. (2010) "Global tectonics ties rocks, quakes and volatiles in the mantle transition zone", The Francis Birch Lecture, Dec. 15, 2010, Am. Geophys. Union, 2010, San Francisco, CA.
- Cormier, V.F., (2009) A glassy lowermost outer core, Geophys. J. Int., doi: 10.1111/j.1365-246X.2009.04283.x.
- Cooper, K. M., John M. Eiler, Kenneth W.W. Sims, and Charles H. Langmuir, 2009, Distribution of recycled crust within the upper mantle: Insights from the oxygen isotope composition of MORB from the Australian-Antarctic Discordance, Geochemistry, Geophysics, Geosystems, Q12004, DOI 10.1029/2009GC002728
- Courtier, A., M. G. Jackson, Jesse F. Lawrence, Zhengrong Wang, Cin-Ty Aeolus Lee, Ralf Halama, Jessica M. Warren, Rhea Workman, Wenbo Xu, Marc M. Hirschmann, Angela M. Larson, Stan R. Hart, Carolina Lithgow-Bertelloni, Lars Stixrude, and Wang-Ping Chen (2007) Correlation of seismic and petrologic thermometers argues for deep thermal anomalies, EPSL, 264, 308-316.
- Dasgupta, R.(2009). Major element and volatile heterogeneity in the Earth's mantle and generation of oceanic basalts. Geochimica et Cosmochimica Acta 73, A265. [KEYNOTE]
- Dasgupta, R., M.G. Jackson, and C.-T.A. Lee (2010). Major element chemistry of ocean island basalts - conditions of mantle melting and heterogeneity of mantle source. Earth Planet. Sci. Lett. 289, 377-392.
- Dziewonski , A. M., Lekic, V., and Romanowicz, B. A., (2010a), Mantle Anchor Structure: An argument for bottom up tectonics, Earth Planet. Sci. Lett., 299, 69-79.
- Gaidos, E., M. Manga, J. Hernlund, and C.P. Conrad (2010) Thermodynamic limits on magnetodynamos in rocky exoplanets, *Astrophysical Journal*, vol. 718, 596-609.
- Green, H. W., W.-P. Chen, and M. Brudzinski (2010) Seismic evidence of negligible water carried below 400 km depth in subducting lithosphere, *Nature*, *467*, 828-831, doi:10.1038/nature0940,.
- Hernlund, J.W. and A.M. Jellinek (2010)Dynamics and structure of a stirred partially molten ultralow velocity zone, *Earth Planet. Sci Lett*., 296: 1–8, (doi:10.1016/j.epsl.2010.04.027).
- Hier-Majumder S., and J. Revenaugh (2010) The relationship between the viscosity and topography of the UltraLow Velocity Zone near the core-mantle boundary, S., Earth and Planet. Sci. Lett., 299, 382-386.

§Höink, T., Lee, C.-T.A., Hawthorne, J., Lenardic, A., 2008. Paleo-viscometry of magma bodies, Earth Planet. Sci. Lett., 267, 100-106.

- Jackson, M. and R. Dasgupta (2008) Compositions of HIMU, EM1, and EM2 from global trends between radiogenic isotopes and major elements in ocean island basalts. EPSL, 276, 175-186.
- Kite, E.S., and V. Lekic, Feasibility of mantle radiogenic power determination with geoneutrinos, in revision for EPSL.
- Konter, J., B. Hanan, J. Blichert-Toft, A. Koppers, T. Plank, and H. Staudigel (2008), "One hundred million years of mantle geochemical history suggest the retiring of the mantle plumes is premature," EPSL, vol. 275, 3-4, 285-295
- Lay, T., Heinz, D., Ishii, M. Shim, S.-H., Tsuchiya, J., Tsuchiya, T., Wentzcovitch, R. and D.A. Yuen (2005) "Multidisciplinary impact of the deep mantle phase transition in perovskite structure", EOS, AGU, Vol. 86, No. 1, 1-5.

•Lee, C. T. and W. -P. Chen (2007) Possible density segregation of subducted oceanic lithosphere along a weak serpentinite layer and implications for compositional stratification of the Earth's mantle, EPSL, 255, 357-366.
•Lee, C. T. A. Courtier, R. Halama, M. Jackson, A. M. Larson, J. Lawrence, Z. Wang, J. Warren, R. Workman, M. Hirschmann, S. Hart, L. Stixrude, C. Lithgow-Bertelloni, W. P Chen (2006) 'The thermal state of the Earth', Fall AGU abstract, V33D-08.
•Lee, C.-T.A., Luffi, P., Hoink, T., Li, J., Dasgupta, R., Hernlund, J., 2010. Upside-down differentiation and generation of a "primordial" lower mantle, Nature, 463, 930-933.
•Lee, C.-T.A., Luffi, P., Chin, E.J., 2011. Building and destroying continental mantle, Annu. Rev. Earth Planet. Sci., 39, 59-90.
analysis of upper mantle structure", Earth and Planetary Science Letters, in revision,
•Manga, M. (2010) Low-viscosity mantle blobs are sampled preferentially at regions of surface divergence and stirred rapidly into the mantle, *Physics of the Earth and Planetary Interiors,* vol. 180, 104-107.
•Matyska, C and D.A. Yuen, "The importance of radiative heat transfer on superplumes in the lower mantle with the new post-perovskite phase change", EPSL, 234, 71-81, 2005.
•Mohit, P. S., C. L. Johnson, O. Barnouin-Jha, M. T. Zuber, & S. C. Solomon (2009), Shallow Basins on Mercury: Evidence of Relaxation?*Earth and Planetary Science Letters*, 285, issues 3-4, 355-363
•Mookherjee, M., Stixrude, L., and Karki, B (2008): Hydrous silicate melts at high pressure. Nature 452, 983-986.
•Mookherjee, M. and Steinle-Neumann, G. (2009) Detecting deeply subducted crust from elasticity of hollandite, Earth and Planetary Science Letters, 288, 349-358.
•Mookherjee, M. and Stixrude, L. (2009) Structure and elasticity of serpentine at high-pressure. Earth and Planetary Science Letters, 279, 11-19.
•Mookherjee, M. and Steinle-Neumann, G. (2009) Elasticity of phase-X at high pressure, Geophysical Research Letters 36, L08307, doi:10.1029/2009GL037782
•Mookherjee, M., and Karato, S. (2010) Solubility of water in pyrope-rich garnet at high pressure and temperature, Geophysical Research Letters, 37, L03310
•Roberts, J. H., R. J. Lillis, and M. Manga (2009), Giant impacts on early Mars and the cessation of the Martian dynamo, Lunar Planet. Sci. Conf. XL, 1265.
•Roberts, J.H., R.J. Lillis, and M. Manga (2009) Giant impacts and the cessation of the Martian dynamo, J. Geophys. Res., 114, E04009, doi:10.1029/2008JE003287.
•Romanowicz, B A (2010) Cooperative Institute for Dynamic Earth Research (CIDER): Contributions to Education, Fall'2010 AGU Meeting (*Invited*) D44A-08.
•Stixrude, L., N. de Koker, N. Sun, M. Mookherjee, B. B. Karki, Thermodynamics of silicate liquids in the deep Earth, *Earth and Planetary Science Letters, 278*, 226-232, doi: 10.1016/j.epsl.2008.12.006, 2009.
•Tseng, T.-L., and W.-P. Chen (2008) Discordant contrasts of *P*- and *S*-wave speeds across the 660-km discontinuity beneath Tibet: A case for hydrous remnant of sub-continental lithosphere, *Earth Planet. Sci. Lett. , 268*, 450-462.
•Uno, H., C. L. Johnson, B. J. Anderson, H. Korth & S. C. Solomon (2009), Mercury's Internal Magnetic Field: Constraints from Regularized Inversions, *Earth and Planetary Science Letters*, 285, issues 3-4, 328-339.
•Xu Yan, Keith D. Koper, Detection of a ULVZ at the base of the mantle beneath the northwest Pacific, GRL, 2009, doi:10.1029/2009GL039387
•Xu, W. C. Lithgow-Bertelloni, L. Stixrude and J. Ritsema (2008) The effect of bulk composition and temperature on seismic structure, EPSL, 275-70-79, doi: 10.1016/j.epsl.2008.08.012