*Institute of
Geophysics and
Planetary
Physics*

*Lawrence Livermore
National Laboratory*

1995 Annual Report

*October 1, 1994 through
September 30, 1995*

*Edited by
Frederick J. Ryerson
Institute of Geophysics and Planetary Physics
University of California*

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UCRL-53809-95

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Acknowledgments

Members of the publication team were Carolin Middleton, publication editor; Frank Marquez, technical illustrator; Torrance Brooksfuller, technical editor; and Jan Tweed, who prepared the manuscript for this report.

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Section I. Overview

The Institute of Geophysics and Planetary Physics (IGPP) is a Multi-campus Research Unit of the University of California (UC). IGPP was founded in 1946 at UC Los Angeles with a charter to further research in the earth and planetary sciences and in related fields. The Institute now has branches at UC campuses in Los Angeles, San Diego, and Riverside, and at Los Alamos and Lawrence Livermore national laboratories.

The University-wide IGPP has played an important role in establishing interdisciplinary research in the earth and planetary sciences. For example, IGPP was instrumental in founding the fields of physical oceanography and space physics, which at the time fell between the cracks of established university departments. Because of its multicampus orientation, IGPP has sponsored important interinstitutional consortia in the earth and planetary sciences. Each of the five branches has a somewhat different intellectual emphasis as a result of the interplay between strengths of campus departments and Laboratory programs.

The IGPP branch at Lawrence Livermore National Laboratory (LLNL) was approved by the Regents of the University of California in 1982. IGPP–LLNL emphasizes research in seismology, geochemistry, cosmochemistry, and astrophysics. It provides a venue for studying the fundamental aspects of these fields, thereby complementing LLNL programs that pursue applications of these disciplines in national security and energy research.

IGPP–LLNL is directed by Charles Alcock and was originally organized into three centers: Geosciences, stressing seismology; High-Pressure Physics, stressing experiments using the two-stage light-gas gun at LLNL; and Astrophysics, stressing theoretical and computational astrophysics. In 1994, the activities of the Center for High-Pressure Physics were merged with those of the Center for Geosciences.

The Center for Geosciences, headed by George Zandt and Frederick Ryerson, focuses on research in geophysics and geochemistry. The Astrophysics Research Center, headed by Charles Alcock, provides a home for theoretical and observational astrophysics and serves as an interface with the Physics and Space Technology Department's Laboratory for Experimental Astrophysics and with other astrophysics efforts at LLNL.

The IGPP branch at LLNL (as well as the branch at Los Alamos) also facilitates scientific collaborations between researchers at the UC campuses and those at the national laboratories in areas related to earth science, planetary science, and astrophysics. It does this by sponsoring the University Collaborative Research Program (UCRP), which provides funds to UC campus scientists for joint research projects with LLNL. The goals of UCRP are to enrich research opportunities for UC campus scientists by making available to them some of LLNL's unique facilities and expertise, and to broaden the scientific program at LLNL through collaborative or interdisciplinary work with UC campus researchers. UCRP funds (provided jointly by the Regents of the University of California and by the Director of LLNL) are awarded annually on the basis of brief proposals, which are reviewed by a committee of scientists from UC campuses, LLNL programs, and external universities and research organizations. Typical annual funding for a collaborative research project ranges from \$5,000 to \$25,000. Funds are used for

a variety of purposes, including salary support for visiting graduate students, postdoctoral fellows, and faculty; released-time salaries for LLNL scientists; and costs for experimental facilities.

Although the permanent LLNL staff assigned to IGPP is relatively small (presently about five full-time equivalents), IGPP's research centers have become vital research organizations. This growth has been possible because of IGPP support for a substantial group of resident postdoctoral fellows; because of the 30 or more UCRP projects funded each year; and because IGPP hosts a variety of visitors, guests, and faculty members (from both UC and other institutions) on sabbatical leave. To focus attention on areas of topical interest in the geosciences and astrophysics, IGPP-LLNL hosts conferences and workshops. IGPP-LLNL also organizes seminars in astrophysics and geosciences. Section IV lists the seminars given in FY 1995.

Figures 1 and 2 give a statistical overview of IGPP-LLNL's UCRP (colloquially known as the mini-grants). Figure 1 shows the distribution of UCRP awards among the UC campuses, by total amount awarded and by number of proposals funded. Figure 2 gives the distribution of awards by center. Final 1995 totals will be reported in our 1996 annual report.

Figure 1. Distribution of FY 1995 UCRP awards to UC campuses from IGPP-LLNL: (a) funds awarded in thousands of dollars and (b) number of projects funded.

Figure 2. Distribution of awards by IGPP-LLNL center.

Since FY 1987, IGPP–LLNL has maintained a bibliography of published research papers resulting from UCRP projects and from research by the IGPP’s staff, postdoctoral fellows, and consultants. These lists are published each year in the annual report. Section V gives the bibliography for FY 1995. As a measure of research productivity, the results are gratifying. The abundance of publications from IGPP collaborative projects is a measure of the significance of the results obtained in these projects. This refereed-journal publication rate for IGPP-related projects corresponds to more than 1 paper/year for each faculty member, 2 papers/year for each IGPP postdoctoral fellow, and 2 papers/year for each IGPP staff member. Figure 3 compares the total papers published in refereed journals or conferences for the last four years. (Note: Because of the extensive peer-review process for most scientific journals, several papers submitted by the principal investigators are still in progress. Therefore, we cannot give an accurate total of 1995 papers published until we receive formal notification from the journals and authors. Final 1995 totals will be available in our 1996 report.)

Figure 3. Total number of papers published in refereed journals and conference proceedings from 1992 through 1995.

Section II. Highlights of Fiscal Year 1995

Center for Geosciences

The primary purpose of the IGPP–LLNL Center for Geosciences is to promote collaborative earth sciences research between LLNL and UC. LLNL's mission-oriented programs in national security and energy research use many subdisciplines within the geosciences. IGPP draws upon these capabilities and expertise and acts as a focal point for research in the fundamental aspects of these areas. We hope to consolidate many unique talents and capabilities at LLNL and provide an identifiable avenue for LLNL–UC Berkeley collaborations. The Center for Geosciences is the focus of these interactions with visitors from academic (UC and other universities), industrial, and government geoscience research institutions. The center's research emphasis on the physics and chemistry of the solid Earth, including seismology, geochemistry, experimental petrology, mineral physics, and hydrology, continues with initiated interdisciplinary studies of active tectonics.

The center is in, and partially supported by, the Geophysics and Global Security and the Geosciences and Environmental Technologies divisions of LLNL's Environmental Programs Directorate (hereafter referred to as the Geosciences Program). It is involved with several programs within the Geosciences Program as well as the Isotope Sciences Division of LLNL's Chemistry and Materials Science Directorate, which is a major contributor of scientific expertise and facilities supporting collaborative efforts in geochemistry. The center provides access to computational, experimental, and analytical research facilities and supports geophysics and geochemistry field studies.

George Zandt and Rick Ryerson share the operations responsibility for the center. Zandt is a seismologist with interests in upper mantle and crustal structure and tectonics and in developing seismic underground imaging techniques. He oversees seismology and observational geophysics research projects. Bill Walter, Howard Patton, and Dan McNamara (LLNL) worked in the seismology group with Zandt. McNamara, a postdoctoral fellow, is working on seismic imaging of the lower crust and mantle beneath Tibet. In FY 1995, as part of our Seismic Exploration of the Deep Altiplano (SEDA) deployment, Annie Kersting (IGPP) worked with Zandt. She took part in a field trip to the Andes.

Ryerson is a petrologist with interests in diffusion in rock-forming minerals, rheology of partially molten crustal rocks, and high-pressure and high-temperature mineral–melt phase equilibria. He oversees geochemistry, mineral physics, and experimental geophysics projects. Ryerson is also involved in Tibet and southeast Asia field studies. James Brenan, Bill Minarik, and Dan Farber are postdoctoral fellows who also worked in the geochemistry group. They performed high-pressure and high-temperature experiments applied to problems associated with lower crustal and upper mantle processes. Henry Shaw, Douglas Phinney, and Ian Hutcheon (LLNL) also played active roles in this research.

The Center for Geosciences is located in an area with minimum access controls. The area houses the center's library, computer workstations, and seismological field equipment for collaborative studies.

The Geosciences Program and Isotope Sciences Division provide facilities for geochemistry and experimental geophysics research. The Isotope Sciences facility has an ion microprobe, an electron microprobe, an inductively coupled plasma (ICP) mass spectrometer, and laboratories for preparing accelerator mass spectrometry (AMS) samples. The Geosciences facility includes apparatus for high-pressure gas media deformation experiments; piston cylinder and multi-anvil laboratories; and laboratories for electrical conductivity measurements and for crystal growth, diamond cell, and cryogenic deformation experiments. It also has laboratories for x-ray diffraction analysis and infrared spectroscopy.

An important change in the Center for Geosciences has been the recent merger with the Center for High-Pressure Physics. This change was made to emphasize the geophysical applications of LLNL's two-stage, light-gas guns. The efforts in this area are headed by William Nellis and a postdoctoral associate, Peter Fiske. In FY 1995, much of their research was focused on investigating crystal structure transformations induced by meteorite impacts.

Research Highlights

The Center for Geosciences has a research program for studying the physics and chemistry of the solid Earth. The research includes seismology, geochemistry, experimental petrology, mineral physics, hydrology, and active tectonics. The following sections summarize some of this research.

Cerium–Lead Fractionation at Convergent Boundaries

The Ce/Pb ratio of about 3 in island-arc basalts (IABs) is similar to the average continental crust, but below the oceanic basalts (about 25) and the bulk Earth (about 10). Cerium and lead have similar bulk solid and liquid partition coefficients and are not significantly fractionated during mantle melting processes. Melt compositions reflect the approximate Ce/Pb ratio of their source regions. The inability of magmatic processes to fractionate cerium from lead suggests that a nonmagmatic process influences the differentiation of the Earth's crust from the mantle. Using low Ce–Pb fluids, generated by the dehydration of subducted oceanic crust, to flux the mantle wedge (the portion of the mantle immediately above the subducted slab) is a favored nonmagmatic process. Since subduction-related magmatism adds low Ce–Pb material to the continents, knowledge of Pb-enrichment in IABs may provide insight into the origin of Pb-enrichment in the continental crust and the complementary depletion of Pb from the oceanic mantle.

In high-pressure experiments, James Brenan, Henry Shaw, and Rick Ryerson confirmed that low Ce–Pb fluids coexist with the dominant mineral phases (garnet and clinopyroxene) produced during high-pressure dehydration of altered basalt. The experiments show that subduction-zone magmas, produced from mantle sources fluxed by basalt-derived fluid, adds Pb-rich, Ce-poor, and mantle-derived material to the continents.

The Ce–Pb composition of lavas from an island-arc suite (Umnak Island in the Aleutian Islands) is consistent with ternary mixtures of components derived from subducted sediment, slab-derived mid-ocean ridge basalt (MORB) fluid, and a mantle wedge with characteristics similar to the

MORB source (Figure 1). By defining the composition of the slab-derived MORB fluid, our new data allow quantitative assessment of the relative contributions of these components to the source region of Umnak lavas. Calculations assumed that the sediment end-member is bulk sediment with 92 ppm Ce and 38 ppm Pb, and that slab-derived MORB fluid has 0.7 ppm Ce and 4.5 ppm Pb. Results show that MORB-derived fluid provides 60 to 97% of weight to the slab-derived component (bulk sediment and MORB fluid) and 15 to 70% of Pb to the Umnak lavas. One may view high-pressure dehydration of subducted basalt as an important mechanism for generating fluids that reduce the Ce/Pb ratio of the overlying mantle wedge. Moreover, subduction of oceanic crust that has lost Pb during dehydration provides a mechanism to increase the Ce/Pb ratio of the oceanic mantle. We conclude that a process acting at convergent margins maintains the complementary nature of the crust–oceanic mantle system with regard to the Ce/Pb ratios.

However, since higher-heat flow is probably typical in the Archean subduction zones, direct melting of basalt may have been a more important process for generating continental crust in the Earth's early history than flux-driven melting of the mantle wedge by basalt-derived fluid. Whether this process can produce the requisite fractionation in the Ce/Pb ratio is uncertain, because of the lack of data about the partitioning of Ce and Pb during the high-pressure melting of hydrous basalt. However, the Archean

Figure 1. Lead isotopic composition as a function of Ce/Pb for: lavas from Umnak Island in the Aleutian Islands (open squares = Recheshnoi, and closed squares = Okmok; data are from Ref. 1); the average north Pacific MORB,¹ which is assumed to be equivalent in Ce/Pb and Pb-isotopic composition as a MORB-source type mantle wedge; the average sediment from DSDP hole 183 (Ref. 2, average Ce/Pb from Ref. 3); and the MORB-derived fluid. (For the MORB-derived fluid, Ce/Pb was calculated using the data in this study; 2 wt% fluid evolved from a source with a garnet/clinopyroxene mass ratio of 60/40). Values on tick marks correspond to the weight percentage of one end member in each binary mixture. The low- $^{207}\text{Pb}/^{204}\text{Pb}$, low-Ce/Pb component that contributes Pb to the Umnak lavas is consistent with the composition of MORB-derived fluid.

tonalite–trondhjemite–granodiorite suite, whose major-element compositions have been reproduced in laboratory experiments on basalt melting, has a low Ce/Pb ratio. This low ratio suggests that hydrous melting of basalt may have generated the Ce–Pb fractionation produced during early crust–mantle differentiation.

Lithospheric Contributions to the Development of Island Arcs

More than 75% of the volcano eruptions above sea level occur parallel to deep oceanic trenches, where cold oceanic material descends into the Earth's interior mantle. At depth, dehydration and melting of the subducted oceanic material ascend into the overlying mantle and cause melting. The magma then migrates toward the surface and forms island-arc volcanoes. This tectonic environment is the principal area for the return of the oceanic crust to the mantle and results in the selective physical and chemical exchange of material between the crust and mantle. As such, island-arc volcanoes are an area for investigating and understanding the Earth's chemical evolution and growth of the continental crust. Although several sources and processes contribute to island-arc magmas, the interactions between the subducting component (oceanic crust, sediment, and fluid), the overlying mantle, and the lithosphere are not understood.

The isotopic composition of the mantle, subducting component, and the overlying arc lithosphere can be distinct and may be used as geochemical tracers to quantify the recycling process between the Earth's mantle and crust. To better understand net chemical fluxes involved in recycling island-arc settings, Annie Kersting (IGPP), Richard Arculus (Australian National University), and Ikuo Kushiro (University of Tokyo) are researching the influence of the lithospheric component on the diversity of island-arc magmas. It is generally accepted that very thick (about 70-km) crustal lithospheres impact mantle-derived lavas, which results in the eruption of more evolved rock types. The notion that thin (30-km) crusts could modify less evolved, more primitive basaltic rocks is controversial. We concentrated on evaluating the chemical effects of thin crustal lithosphere on the modification of primitive erupted rocks.

Northeastern Honshu, Japan, makes this experiment possible. In northeastern Honshu, the current transect of active arc volcanoes lies on two different crustal terranes (Figure 2). In northern Honshu, the Tanakura Tectonic Line (TTL) is a lithospheric-penetrating fault that crosscuts the transect of volcanoes. In this tectonic location, parameters that may influence the chemistry of the volcanoes—such as depth to the subducting slab, distance to the trench axis, crustal thickness, and composition of the mantle, subducting sediments, and oceanic crust—are constant. Isolating these parameters leaves the juxtaposition of distinctive crustal lithospheres, along the transect of arc volcanoes, as the remaining petrogenetic variable. Therefore, isotopic and elemental distinctions that are coincident with the TTL must reflect differences in the contribution from the overlying lithosphere.

Figure 2 shows that the volcanoes from the TTL transect have isotopic differences coincident with the TTL. The volcanoes south of the TTL (shown in open symbols) have elevated Pb compared with the volcanoes to the north (solid symbols). Isotopic patterns for Sr and Nd (not shown) are consistent with the Pb isotope data. Both volcanic groups are distinct from mantle values, shown in Figure 2 as Pacific MORB. The Pb isotopic composition of oceanic sediments east of northern Honshu exceeds the TTL transect, making us doubt that mixing subducted sediments with a mantle

Figure 2. Location of volcanoes in northeastern Honshu, Japan (solid triangles). The transect of Honshu volcanoes is crosscut by the TTL Fault, separating two distinct tectonic terranes. Mount Fuji is situated on a third crustal terrane, which is younger than the Abukuma and Tamba terranes. The triangles on the oceanic trenches indicate the direction of the subducting oceanic crust.

source could account for the distinct signatures of the data. Contamination of the crustal lithosphere, as the magmas traverse through chemically distinct crusts, causes the different geochemical signatures between the volcanoes that are north and south of the TTL.

Figure 3 shows the analyzed samples from Mount Fuji, located on a third crustal terrane in Honshu. The Pb isotopic signature of Mount Fuji is distinct from the TTL transect and elevated compared with the signature for Pacific MORB. The Pb isotopic signature is more similar to that for lavas north of the TTL. The new data strengthen the argument that mixing of mantle-derived basalts with lower crustal reservoirs is an important process in island-arc volcanism. This work demonstrates that thin lithosphere is an active geochemical filter for traversing magmas, resulting in significant modification of primary mantle melts.

Be–Li–B Fractionation in Magmas

Beryllium, lithium, and boron are associated with sediment contributions to island-arc lavas. To interpret the sediment flux based on the compositions of subduction zone magmas, we must determine the fractionation of these elements during mantle melting. In FY 1995, Elizabeth Neroda (a student from Occidental College), Henry Shaw, James Brenan, Rick Ryerson, and Craig Lundstrom (UC Santa Cruz) completed experiments that determined the partition coefficients between major mantle minerals and basaltic melts (Figure 4). Experiments were conducted at 1 atm (olivine and

Figure 3. Lead isotopic data for the TTL transect and Mount Fuji. Data from the volcanoes north of the TTL are shown by filled symbols, and those from the volcanoes to the south are shown by open symbols. The Pb isotopic composition of the mantle is shown by Pacific MORB (crosses).⁴ Pacific sediments⁵ collected east of Honshu are also shown. Two other island arcs, Kamchatka⁶ and Marianas,⁷ are shown for comparison.

Figure 4. Results of mineral–melt partitioning experiments for beryllium, lithium, and boron between basaltic melt and olivine (ol) or clinopyroxene (cpx) as a function of nonbridging oxygen over tetrahedrally coordinated cations (NBO/T).

clinopyroxene) and 1.5 GPa (pargasite) using mostly basaltic melt compositions. For each composition, suitable time–temperature histories were used, which resulted in large ($+50\text{ }\mu\text{m}$) homogeneous crystal growth (compare our results with those of Brenan et al.⁸). After quenching, the run products were sectioned, polished, and analyzed for major and trace elements by electromagnetic pulse (EMP) and secondary ion mass spectrometry (SIMS).

These results, combined with a simple batch melting model (residual modes of 60:30 olivine to orthopyroxene and 0 to 10% clinopyroxene or amphibole and assuming $D_{\text{olivine}} \sim D_{\text{orthopyroxene}}$), allowed us to assess the role of melting on B–Be–Li fractionation. Calculations indicate that although the B/Li and Be/Li ratios in mantle-derived melts (0.5 to 20%) will be fractionated with respect to their source, the B/Be ratio in the melt records the source value throughout the melting interval (Figure 5). According to the observations of Ryan and Langmuir,^{9,10} if the degree of melting is greater than 5%, calculations indicate that the Be/Nd and B/K ratios will record their source.

Lithological Partitioning of Fluids Due to Differing Interfacial Energies

We are studying the grain-scale distribution of H_2O -rich fluids and silicate melts in mantle and lower crustal rocks to characterize how small fractions of fluid or melt become mobile. Complementing the IGPP studies of the equilibrium distribution of trace elements, James Brenan, Bill Minarik, and Rick Ryerson have been studying the microstructure of two-fluid systems (silicate melt and hydrous fluid) and the segregation of these fluids between lithologies.

Figure 5. Results of melting calculations showing the effects of mantle partial melting on B/Li, B/Be, and Li/Be ratios in derived magmas. The numbers on the lines give the percentage of amphibole in the residuum.

A fluid contacting a solid mineral will have an energy associated with the interface, which will depend on the composition of the mineral and fluid. A system with several mineral types will attempt to distribute the fluid so the energy is minimized. Minerals with low solid-fluid energy will have larger surfaces contacting the fluid than will minerals with higher solid-fluid energies. A larger proportion of the minerals with a low solid-fluid energy will contain a larger fluid-filled porosity and will have zones of higher permeability to fluid transport.

We found that olivine-rich layers develop a high porosity when they contact other mantle minerals, including pyroxenes, amphiboles, and micas (Figure 6). Areas of the olivine-rich (dunites and harzburgites) mantle, such as residual assemblages from a prior melting event, reaction zones, or cumulates from solidifying melt, will enhance permeability. Quartz in lower-crustal assemblages plays a similar role: quartz-rich lithologies will partition fluid from amphibole, mica, or pyroxene-rich lithologies. The leucosomes (quartz- and feldspar-rich) of layered metamorphic rocks will be layers of enhanced permeability to fluid flow and fluid will be channeled parallel to these layers. We hope that our increased understanding of fluid distribution and fluid transport will help us understand the implications of the chemical alterations and trace-element patterns found in rocks.

Figure 6. A backscattered electron image of a polished section of an experiment. Two mineral powders (olivine on the left and clinopyroxene on the right) were combined with 3.3 wt.% water in a gold capsule and were run at 1.5 GPa (15 kb) of pressure and a temperature of 1050 °C for six days. During the run, water was expelled from the clinopyroxene layer into the olivine layer to minimize the interfacial energy of the system. The olivine layer now contains about 17 vol.% porosity compared with about 8 vol.% porosity in the clinopyroxene layer. The difference also indicates that water has increased the rate of olivine grain growth, because both powders started with similar grain sizes. Porosity remains in the clinopyroxene layer as isolated pockets, with the fluid trapped by dry grain edges.

Very High-Pressure Sulfide-Melt Textures in Mantle Assemblages

Using the large-volume multi-anvil press facilities at LLNL, Bill Minarik and Rick Ryerson are investigating the microstructure and chemical composition of sulfide melts in silicate minerals at pressures up to 17 GPa (170 kb), corresponding to depths of 500 to 600 km. These depths correspond to the transition zone in the mantle, where minerals at shallower depths transform into denser forms. It is believed that the final transformations of these minerals occurs at 670 km in the Earth, below which the minerals remain unchanged to the boundary of the Earth's core (at a depth of 2885 km and pressure of 136 GPa). Large-volume experimental apparatus cannot reach the extreme conditions of the Earth's core, but by studying minerals and melts of similar high-pressure structure, we hope to understand the formation and properties of this high-pressure portion of the Earth, which forms 74% of the Earth's volume.

We investigated the textural microstructure of iron–nickel–sulfur melts contacting olivine, pyroxene, and the modified spinel polymorph of olivine. The experiments were conducted at 1500°C and at pressures ranging from 1 to 17 GPa. For compositions that are more metal-rich than the monosulfide, including the eutectic composition, the metal sulfide melt has a dihedral angle greater than 60 deg and does not form an interconnected grain-edge fluid. High pressures do not measurably alter the dihedral angles. Textural evolution coarsens the sulfide melt pockets, which results in large pockets being surrounded by silicate grains and separated by melt-free grain edges. Lattice and grain-boundary diffusion limits the chemical communication between these large pockets (Figure 7).

Figure 7. A backscattered electron photo of sulfide melt within an olivine and orthopyroxene matrix, contained within a graphite capsule (1 GPa, 1500°C, 2 days). The bright sulfide melt (8.5 vol.%) is excluded from grain boundaries and restricted to grain corners and has shown no tendency to segregate from the silicate matrix. Several sulfide pockets have coarsened and are enclosed by more than four silicate grains.

The energy relationship between sulfide melt and silicates prevents the separation of sulfide melts from solid silicate, through grain-boundary percolation, so they remain stranded in isolated melt pockets. Sulfide melt in excess of the critical melt fraction (5 to 25%) will develop a transient interconnectivity as sulfide collects into larger melt pockets and interconnectivity ends. Efficient separation of metal-sulfide melts to form the Earth's core from the silicate mantle requires substantial melting of the silicate matrix. This implies that most of the Earth was molten, which is consistent with estimates of the energy released by the impact of large planetoids early in the Earth's history.

The Southern Sierra Nevada Continental Dynamics Project

Mount Whitney, located within the Sierra Nevada in central California and the highest peak in the conterminous United States, lies less than 150 km from the lowest elevation—Death Valley. Crustal thickness and upper-mantle velocities beneath the region are poorly understood and thus have complicated the study of tectonic processes, which are responsible for the recent uplift of the Sierra Nevada. Previous seismic investigations of the Sierran crust and mantle have been unable to resolve two end-member models: isostatic crustal compensation by a crustal root of 55 to 65 km, or a thin crustal root of 30 to 35 km overlying a warm and buoyant asthenosphere associated with crustal extension to the east of the Sierra Nevada.

As part of an effort to solve this problem, Stan Ruppert (IGPP) has been participating in the Southern Sierra Nevada Continental Dynamics (SSCD) project. The seismic refraction survey, conducted in September 1993, attempted to resolve the controversy about the crustal structure of the Sierra Nevada. This seismic study used three profiles: (1) a 325-km-long north-south profile extending from east Mono Lake and southward across the Garlock Fault; (2) a 400-km-long east-west profile extending from Death Valley and westward across the Sierra Nevada Mountains to the San Andreas Fault; and (3) a 480-km-long east-west profile for the 1.3-kt chemical explosion (the Department of Energy's Non-Proliferation Experiment) at the Nevada Test Site recorded from Beatty, Nevada, nearly to the Pacific Ocean. For each profile, 675 seismic recorders were installed along the ground to record the travel-time data needed to model the three-dimensional velocity structure and thickness of the crust of the Mesozoic Sierra Nevada batholith and the adjacent Great Valley and western Basin and Range Province in southern California.

Three-dimensional, finite-difference travel-time inversion of P_g and P_n arrivals reveals low crustal velocities in the Sierra Nevada and Basin and Range (6.0 to 6.4 km s⁻¹ in the upper crust, 6.2 to 6.6 km s⁻¹ locally, up to 6.8 km s⁻¹ in the lower crust) and low upper-mantle velocities (7.6 to 7.8 km s⁻¹). The crust thickens from southeast to northwest along the axis of the Sierra Nevada from 27 km in the Mojave Desert to 45 km in the western Sierra Nevada. Based on the three-dimensional seismic analysis, a crustal root (a region of local crustal thickening 6 to 8 km), centered 80 km west of the Sierran topographic crest to the Sierra Nevada, is north of the west-east line (High Sierra), but not aligned with the highest topography.

A previous three-dimensional P-wave tomographic upper-mantle velocity study shows a high velocity (+5%) upper-mantle anomaly from 50 to 250 km deep that underlies the imaged Sierran crustal welt. An adjacent low-velocity (-3%) upper-mantle anomaly centered beneath the Sierran crest is a major regime of asthenospheric downwelling flanked by peripheral

regions of asthenospheric counterflow related to the passage of the Mendocino Triple Junction. A density model derived from the crustal velocity model, with constant mantle density, satisfies the pronounced negative Bouguer anomaly associated with the western Sierra Nevada. Also, the model shows a large discrepancy in the eastern Sierra Nevada, increasing to 100 mGal in the Basin and Range Province. Matching the observed gravity with anomalies in the crust is not possible with realistic densities. Therefore, to develop a plausible model, we must include a contribution from the upper mantle. The region of low P_n , the upper-mantle velocity anomalies, and the absence of a thick isostatic crustal root centered beneath the Sierran crest suggest that the asthenospheric upwelling or lithospheric thinning under the Basin and Range Province and eastern Sierra Nevada caused, and supports, the recent uplift of the Sierra Nevada.

The Gangdese and Renbu-Zendong Thrust Systems: Lateral Extent and Slip History

In eastern Tibet, the Indus-Tsangpo suture, the boundary between India and Asia, is defined by the juxtaposition of rocks of the Gangdese batholith on the north and Tethyan metasediments on the south. The north-dipping Gangdese Thrust (GT) and the Renbu-Zedong Thrust (RZT) mark the contact and obscure the trace of the older GT over much of this region. K-feldspar thermochronometry in this region has constrained slip along the GT, which was active between 27 and 23 Ma. This slip history is consistent with cooling ages observed in GT hanging wall rocks to the north. Similar data collected from samples within the footwall of the RZT are consistent with fault activity occurring between 19 to 15 Ma and perhaps as late as 11 Ma.

West of Xigaze, the Xigaze forearc group is preserved as a pop-up feature, bounded by north- and south-dipping thrusts on its south and north sides, respectively. North of the suture, the Gangdese plutonics are replaced by their volcanic equivalents. Rick Ryerson (IGPP-LLNL) and Mark Harrison, An Yin, and graduate student Mike Murphy (IGPP-UCLA) speculated that the Xigaze bounding thrusts are related and represent the westward extension of a collision-zone-wide GT system (GTS). Preservation of the Xigaze Group and Linzizong volcanics (the volcanic equivalent of the Gangdese plutonics) suggests that the amount of GTS displacement decreases west of Xigaze. Contemporaneous displacement east and west of Xigaze is a necessary condition of this hypothesis. Since the temperatures of the minerals comprising the hanging wall rocks were likely below that of the argon closure interval prior to displacement, determining the time displacement is more difficult in this region than in the more deeply eroded rocks to the east. Hence, this research concentrated on dating cross-cutting relationships and suture zone molasse deposits, which may be associated with GT-related uplift.

Near Dazugka, molasse deposits lie on the Gangdese plutonics. The molasse contains cobbles of poorly consolidated Gangdese granite and plant fossils as evidence of low temperatures experienced by this deposit. Argon-argon thermochronometric analyses of K-feldspars from the granitic cobbles within the molasse record rapid cooling from about 300°C beginning at 22 Ma. Prior to 22 Ma, the temperature was greater than that recorded in the basin. Therefore, the thermal history must represent rapid cooling in the cobble source region and places an Early Miocene upper age constraint on the molasse.

Cross-cutting relationships northwest of Xigaze, where the GTS back-thrust is cut by undeformed dacitic dikes and sills, lower the age of the GTS displacement. An Ar–Ar age of 18.3 ± 0.5 Ma for a hornblende from these rocks indicates that displacement along the GTS was finished. With the constraints obtained near Dazugka, these data indicate that active thrusting along the GT west to Xigaze is contemporaneous with that observed to the east.

Near Kailas, Gangdese plutonics are overlain by conglomerates (Figure 8). Recent mapping indicates that the RZT (which comprises south-dipping imbricates) is the predominant feature in this area, thrusting Tethyan ophiolites and metasediments north, over the Dazugka Formation, and transporting slices of the Dazugka to the north. The GTS is not exposed. Cobbles of the Gangdese plutonics dominate the basal section of the molasse, replaced by cobbles of metasediments, cherts, and ophiolite. Thermochronometric analysis of K-feldspars beneath the unconformity indicates rapid cooling at 27 Ma, similar to that observed east of Xigaze. Granitic cobbles in the footwall of the RZT are characterized by relatively flat Ar age spectra from 11 to 20 Ma. An argon loss caused by reheating within the RZT footwall subsequent to deposition explains the difference in age spectra between the Gangdese bedrock and the cobbles derived from it. The structures, age constraints, and variation in cobble composition suggest that the Kailas Basin received sediments from the denudation of the Gangdese batholith as a result of uplift by the truncated GTS. Tethyan cobbles were subsequently deposited by southward loading of the basin and denudation of Tethyan rocks, which resulted from movement along the RZT with associated reheating of its footwall.

The thermochronometric data constrain the age of suture-zone molasse deposits to no older than Oligocene, more likely Early Miocene. The ages of these deposits, coupled with cross-cutting relationships, support collision-zone-wide Early Miocene movement along the GTS. The decreased displacement along the GTS between 84 and 89°E, where the Xigaze group is preserved, suggests that thrusting south of the suture may have accommodated the convergence in this region.

High-Strain-Rate Shock Experiments and the Origin of Pseudotachylite

During FY 1994 and 1995, we have conducted experiments in which we shock-loaded samples of single-crystal quartz to pressures from 10 to 56 GPa. These experiments use a novel sample recovery design that allows the material to undergo enormous strain yet be recovered intact. We believe this method faithfully reproduces the effects of impact on rocks in the central part of large impact craters.

Samples held in high-strain-rate recovery fixtures and shocked to pressures from 42 to 56 GPa showed a pattern of radial and concentric fractures filled with a frictional melt made up of Al and Si. Samples held in steel fixtures and shocked to the same pressures did not undergo as much strain and showed no systematic radial and concentric fractures nor any melted material.

Our results suggest that plastic deformation and the production of pseudotachylites may be an important process in meteorite impacts. Our highest pressure sample contained from 1 to 2% Si by weight. Transmission electron microscope images suggest that the Si represents 10 to 20% of the volume of the pseudotachylite-like material produced. Thus, a substantial

Figure 8. Bedrock geology of the region near Mount Kailas.

fraction of the total sample may have been pseudotachylite. The formation of dense networks of Type A pseudotachylites in the central portions of impact structures may leave the rocks hotter than is predicted from Hugoniot measurements or post-shock temperature measurements. This temperature may cause the central portions of large impact structures to have a substantial static thermal metamorphic overprint. Also, friction melting may be an important contribution to the total volume of impact melt in larger craters and may explain the increase in the proportion of impact melt with crater size.

The Shock Phase Transformation of Zircon to the Scheelite Structure

Zircon (ZrSiO_4) is a common accessory mineral in crustal rocks. It undergoes a first-order crystalline-to-crystalline phase transition to the scheelite structure under compression at high temperature, under compression at room temperature, and under shock compression. Despite the rapid kinetics of this phase transition, the scheelite phase is metastable to high temperature at 1 bar. We believe zircon may be excellent as a shock geobarometer and geothermometer in natural systems.

We conducted shock recovery experiments on single-crystal zircon up to 52 GPa. Our experiments show that shock compression lasting about 0.1 ms produces 1 to 2% scheelite phase at 20 GPa, 10 to 15% at 30 GPa,

and 100% conversion at 52 GPa. X-ray diffraction (XRD) patterns of the scheelite-phase show line broadening 4 times that of zircon. The ^{29}Si magic angle spinning (MAS) nuclear magnetic resonance spectra of the scheelite phase consist of a single peak at -90.5 ppm, 9 ppm more shielded than the Si site in zircon. However, the peak is not broader than that for zircon, suggesting that the short-range structural disorder does not dominate the residual strain in the scheelite phase.

We conducted thermal reversion experiments at 1 bar. After 256 hours at 800°C , we found that the scheelite phase does not measurably revert to zircon. We predict that the scheelite phase of ZrSiO_4 is in shocked rocks from terrestrial impact craters and that it may provide a better measure of peak shock pressure in rocks. We are searching for this phase by extracting zircons from Meteor Crater, Arizona.

Large-Scale Impact Experiments Using the Super-High-Altitude Research Project Gun

The Super-High-Altitude Research Project (SHARP) gas gun, the largest two-stage light-gas gun, is used as a hypersonic research facility. Projectiles weighing from 1 to 10 kg are fired horizontally into air past high-speed diagnostic equipment (roughly a 20-m flight path) and into a concrete bunker filled with sand. Recent experiments of hypervelocity scramjet provided the opportunity to conduct a hypervelocity impact experiment.

We measured the temperature of the ejecta at intervals as it approached the bunker. Our results show that the more distal ejecta is hotter, about 20°C , although the effects of entrainment of local material and turbulent mixing inside the bunker complicated this measurement. Also, we measured the post-impact topography and excavated the target area. We found fine gray dust covering isolated small fragments of white, friable, shock-consolidated sand on white shock-comminuted sand, which graded into undeformed sand. XRD analysis of the fine gray dust showed a peak for quartz with a trace of Al (the principal constituent of the scramjet). We found no evidence for oxidation of the Al to Al_2O_3 , and no tektites or microtektites were found in the ejecta. We estimate that 10% of the impact energy remains in the sand as heat. Comparing the crater size to the predicted smooth-particle hydrodynamics calculations shows that the computer simulations do not adequately account for frictional heating and irreversible changes in the sand and overestimate the size of the final crater.

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Astrophysics Research Center

The Astrophysics Research Center serves the aims of IGPP–LLNL in astrophysics. These goals include managing the astrophysics part of the UCRP and facilitating contacts between UC scientists and their LLNL counterparts. The Astrophysics Research Center also serves as the focus of astrophysics activities at LLNL by organizing the weekly astrophysics colloquium, by hosting visitors and collaborators, by editing an annual Observatory Report that covers astrophysics activities at LLNL (and is published in the *Bulletin of the American Astronomical Society*), and by providing a variety of other service functions. The staff and postdoctoral researchers of the Astrophysics Research Center carry out a significant program of research.

The scientific staff of the center are Charles Alcock (Center Head), Kem Cook, Claire Max, and Willem van Breugel. Administrative support is provided by Christina Budwine (Operations Manager), and by secretaries Jan Tweed and Valerie Knighten. Debbie Santa Maria manages the network of computers in the center.

Postdoctoral fellows perform most of the research in the Astrophysics Research Center. Some fellows are supported entirely by IGPP funds, while some are supported partially by other groups at LLNL. In FY 1995, the postdoctoral fellows were David Bennett (Notre Dame), Leigh Brookshaw (Yale University), Arjun Dey (UC Berkeley), Michael Gregg (Australian National University), Karsten Jedamzik (UC San Diego), Bruce Macintosh (UC Los Angeles), Stuart Marshall (UC San Diego), Ed Moran (Columbia University), Sun Rhie (Stanford University), Adam Stanford (University of Washington), and Christopher Skinner (University of Manchester).

The center hosts several scientific visitors, not only from the UC campuses but also from around the world. These visitors stay for a day to a year. Some who are affiliated with local institutions spend large, ongoing portions of their time in the center.

The center and its offices are in Building 319, which is close to the offices of many LLNL astrophysicists and is subject to minimal access controls. These features make the center ideal for the many collaborations that have developed between UC researchers and LLNL scientists.

The Astrophysics Research Center has access to a variety of machines for computing. Most day-to-day work, which includes code development, image processing, and symbolic manipulation, is carried out on the center's network of Sun workstations. This network has been used for large-scale processing by the exploitation of codes that utilize a large fraction of the network for parallel processing. This level of processing is especially effective at night, when most of the network is otherwise quiet and when the "invasive" code will not adversely affect the image-processing work. In addition, much greater computing power is available in other parts of LLNL.

Research Highlights

The Astrophysics Research Center has developed a research program that exploits the traditional strengths in astrophysics at LLNL and opens new areas of study. This research ranges from smaller-scale theoretical and observational projects to large collaborative ventures. The following pages summarize some of this research.

Laser Guide Stars

Claire Max, Scott Olivier, Jim Brase, Don Gavel, Bruce Macintosh, and Herbert Friedman, working with four LLNL collaborators and five collaborators from three UC campuses, are developing laser guide stars for astronomical adaptive optics. The goal of this project is to improve the angular resolution achieved at ground-based observatories. If the project is successful, the angular resolution at major observatories might be improved by 10 to 100%.

The angular resolution of ground-based telescopes with apertures larger than 10 to 20 cm is limited to about a second of arc because of turbulence in the atmosphere. In principle, if one deforms a flexible secondary mirror to make the wavefront nearly flat, then adaptive optics can be used to correct for the wavefront distortions, which are measured with a wavefront sensor. This correction would allow ground-based telescopes to be operated at or near their diffraction-limited bounds. For example, at a wavelength of 0.5 μm , the diffraction-limited resolution would be 0.04 arcsec for a 3-m telescope and 0.01 arcsec for a 10-m telescope. These represent improvements in resolution of factors of 25 and 100, respectively, relative to the atmospheric resolution of about 1 arcsec.

To correct the visible range, one needs a bright reference object within a few arcseconds of the object being imaged. The statistics of bright stars are such that a few percent of the sky is accessible for diffraction-limited viewing, using nearby bright stars as the wavefront reference.

To make up for the lack of bright reference stars, this consortium is developing the ability to produce artificial stars using a powerful laser. The idea is to use a laser tuned to the sodium D lines to resonantly excite the atmosphere sodium layer at 90-km altitude, which makes an artificial star to serve as a reference beacon. A wavefront sensor detects the tilts of the reference wavefront, and a wavefront computer uses the reference wavefront to calculate the adaptive-optics corrections. Finally, the correction is applied to a deformable mirror. The images recorded using the deformable mirror, with the telescope's primary mirror, will have most of the atmospheric distortions removed.

The team installed a 20-W dye laser on a 3-m telescope. This laser is based on technology developed for the LLNL Atomic Vapor Laser Isotope Separation (AVLIS) program. The laser produced an eighth to ninth magnitude artificial guide star, sufficient for adaptive optics correction of the 3-m telescope at wavelengths of 1 to 2 μm .

An LLNL-developed adaptive optics system was tested on the 3-m telescope. It corrected atmospheric turbulence to produce near-diffraction-limited images in the near infrared, using a bright natural star as a wavefront reference. The process of integrating this system with the artificial star produced by the laser is ongoing. Preliminary results show a sharp reduction in the atmospheric turbulence power spectrum. We found that noncommon-path optical errors, calibration, and the difference in focus between the sodium layer and stars at infinity limit the quality of the returned images. We are upgrading the system to deal with these issues. The first diffraction-limited laser-guide-star adaptive optics images are expected in 1996.

Bruce Macintosh (IGPP) and collaborators at UC Berkeley and UC Los Angeles plan to use this system in natural guide star and laser guide star mode. Projects include searches for brown dwarf companions to young stars, studies of young stellar objects such as T Tauri stars, and imaging of active galactic nuclei. Only the LLNL laser makes these studies possible.

Professor James Graham (UC Berkeley), in collaboration with Bruce Macintosh, is constructing a diffraction-limited, near-infrared camera specifically for use with the adaptive optics system. The LLNL group is also working on the adaptive optics and laser guide star system for the 10-m Keck telescope in Hawaii.

The Massive Compact Halo Objects Project

The Massive Compact Halo Objects (MACHO) Project is an experimental search for the dark matter, which makes up at least 90% of the mass of our galaxy. It was initiated at LLNL and involves Charles Alcock, Robyn Allsman, Timothy Axelrod (now at the Mount Stromlo Observatory), David Bennett (now at Notre Dame), Kem Cook, and Hye-Sook Park of LLNL; Stuart Marshall (now at LLNL) and Christopher Stubbs of the Center for Particle Astrophysics at the University of Washington; Kim Griest of the Center for Particle Astrophysics at UC San Diego; Will Sutherland at Oxford University; and Kenneth Freeman, Bruce Peterson, Peter Quinn (now at the European Southern Observatory), and Alex Rodgers of the Mount Stromlo and Siding Spring Observatories in Australia.

Dark matter is distributed in a large, spherical halo. Its constitution is unknown, because it emits no detectable radiation. Most hypotheses for its constitution involve speculations from particle physics. The experiment searches for planets, brown dwarfs, and black holes or any other massive objects (MACHOs) having a mass range of $10^{-7} M_{\odot} < M < 1 M_{\odot}$.

If the dark matter consists of MACHOs, it will occasionally magnify light from extragalactic stars by the gravitational lens effect. An event can be recognized by fitting a theoretical light curve to the observations (three-parameter fit) and by its lack of color variation (it is achromatic). Unambiguous recognition by microlensing requires adequate data points on the light curve (10) and measurements in at least two filter bands. To detect events, one must monitor millions of stars for several years. We wanted to detect at least 10 events (maxima greater than 0.25 magnitude, more than 10 points per light curve, good three-parameter fit, and no color variation) per year. The experiment will operate for at least four years.

The MACHO Project is operating with the 130-cm reflecting telescope of the Mount Stromlo Observatory, near Canberra, Australia. Operating at prime focus with an innovative optical system gives a field of view 1 deg in diameter. We used a dichroic filter for simultaneous imaging in two spectral bands, doubling the effective exposure rate. The beams leaving the beam-splitter are imaged onto mosaics of four 2048- × 2048-pixel charge-coupled devices (CCDs). The typical exposure is 300 s, followed by about 60 s to read the CCD chips. The experiment generates more than 4 Gbytes of data per night. A dedicated computer system and software process the data. This system measures, twice per night, the brightness of stars in the Large Magellanic Cloud. Measuring in the regions at the central bar in the Large Magellanic Cloud, the system can record more than 500,000 stars in one image. In the more eroded regions near the center of the Milky Way, the system can record more than 600,000 stars in one image.

The system had some spectacular successes in FY 1995. We estimate that about 20% of the dark matter is made up of MACHOs. Additional data should refine this estimate.

Searching for Asteroids

Kem Cook (LLNL), Christopher Stubbs and A. Diercks (University of Washington), and Ted Bowell and B. Koehn (Lowell Observatory) are completing an innovative 4096×4096 -pixel scanning CCD camera, which will operate at prime focus on a 24-in. Schmidt telescope on Anderson Mesa in Arizona. This camera, thermoelectrically cooled, will scan the sky along great circles of declination at up to 12 times the sidereal rate. This system, the heart of the Lowell Observatory Near Earth Object Survey (LONEOS), allows about 1000 square degrees per night to be triple-scanned to detect near-Earth objects through their rapid apparent motion.

X-Ray Emission from the Starburst Galaxy M82

It is generally assumed that the dominant sources of x-ray emission in galaxies undergoing intense bursts of star formation are the same as those in the Milky Way: stars, accreting binary star systems, supernova remnants, and hot phases of the interstellar medium. During the last decade, a hot, gaseous, outflowing wind has been found in these galaxies. An x-ray image of the starburst galaxy M82, obtained with the ROSAT Observatory, shows the wind (Figure 9). The optical image in Figure 9a shows that M82 is a peculiar disk galaxy. The overlaid contours, which map the total intensity of M82's x-ray emission, reveal that x rays originate from regions outside the plane of the galaxy. The kinetic energy from exploding stars drives the hot wind. The gray-scale image in Figure 9b indicates the ratio of high-energy to low-energy x rays emitted at each position in the galaxy (dark means a high ratio) and shows that the nuclear region of M82 is a copious source of high-energy x rays. This information, with the broadband x-ray spectrum of M82 obtained with the Advanced Satellite for Cosmology and Astrophysics (ASCA) satellite, reveals that these high-energy x rays are not associated with the wind. The most plausible source for the hard-x-ray component in M82 is the galaxy's infrared radiation, energized to x-ray wavelengths through interactions with supernova-generated relativistic electrons. This process has been suspected to be in starburst galaxies.

Galaxy Clusters at High Redshift

Observations of high-redshift clusters of galaxies have resulted in tantalizing insights into the evolution of galaxies in rich environments and of the most massive collapsed peaks in the spectrum of cosmological matter fluctuation. The advent of modern, large-format optical and infrared array detectors and multi-object spectrographs has provided a wealth of new data on distant clusters and the spectral properties of the galaxies they contain. The number of high-redshift clusters is remarkably small, however, primarily because spectroscopy of faint galaxies is so challenging. However, by choosing from a large complement of narrow and intermediate band filters, it is possible to measure low-resolution "spectra" of large numbers of galaxies, identifying their spectral properties.

IGPP postdoctoral fellow A. Stanford is expanding on this method by extending the visual region imaging into the near-infrared, taking advantage of new, large-format infrared detectors at the National Optical Astronomy Observatories, to better identify cluster members and to study galaxy evolution. One of the clusters he is currently studying is C0024+17 at a redshift $z = 0.391$. This cluster acts as a gravitational lens for background objects. Figure 10 shows the central arcminute of the cluster, with five images of the

Figure 9. (a) Contours of the total x-ray intensity of the nearby starburst galaxy M82, overlaid on an optical image, demonstrate the presence of a starburst-driven outflow of hot gas from the galaxy. (b) The ratio of high-energy to low-energy x rays emitted from each position in M82 indicates that the emission from the nucleus of the galaxy is dominated by high-energy (or hard) x rays, whereas the emission from the extended wind is comparatively much softer.

Figure 10. A Hubble Space Telescope image of the galaxy cluster C0024+17, which acts as a gravitational lens for a background galaxy.

same background galaxy in the form of arcs and arclets centered around a compact group of galaxies. The lensed galaxy appears as elongated rings with several prominent knots. Current multicolor visual and near-infrared observations of C0024+17 are being analyzed to determine whether this cluster is in any way special in its galaxy type content (ellipticals and spirals) and evolutionary state.

Section III. Research Summaries of Collaborative Projects

Astrophysics

A Very Large Array Survey of the Sky at 1400 MHz

Principal Investigator: Robert Becker (UC Davis)

LLNL Collaborator: Wil van Breugel

The Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey completed the analysis of the second season of observing and provided a catalog of 138,000 discrete radio sources for 1550 square degrees of sky. Comparisons with existing databases confirm the astrometric accuracy of the survey catalog. A number of scientific studies have been initiated, including a bright quasar survey, research for a distant cluster of galaxies, and an investigation of large-scale structure in the universe.

Abstract

The primary objective of this project is to create an accurate, high-dynamic range image of the radio sky at 1400 MHz. This survey will serve as a fundamental resource for astrophysics research and will have immense value for studying extragalactic objects at high redshifts, a primary research interest within IGPP–LLNL. Using the survey to find distant objects, we hope to study the evolution of quasars, radio galaxies, clusters of galaxies, and the universe.

Objectives

A number of studies are now under way. Our bright quasi-stellar object (QSO) survey is the most advanced, with 70 quasars in the 300-square-degree area of the 1993 data observed. We have been awarded telescope time at the Lick Observatory to extend the survey to the 1200-square-degree area covered in 1994. By the summer of 1996, we will have discovered a sample of about 350 quasars, enough to start making definitive statements about quasar evolution.

Progress

The FIRST survey revealed a new class of radio sources with extremely high variability. With several days separation, the survey observed every source at least twice. We found about 300 sources that varied by 25 to 100% over several days, a phenomenon not previously observed. We carried out two-point correlation analysis on the radio catalog and found strong evidence for clustering between 0.1 and 1.0 deg. This is the first detection of clustering in radio sources and is important because the radio sources lie at greater redshift than the optical galaxies that have been studied. Hence, the radio source correlations will probe large-scale structure at an earlier epoch in the history of the universe.

Numerical Studies of Fragmentation in Star-Forming Regions

Principal Investigators: Christopher F. McKee (UC Berkeley) and Richard I. Klein (LLNL and UC Berkeley)

LLNL Collaborators: John Bell, Louis H. Howell, and Jeffrey Greenough

Other Collaborator: Tod Woods (Lawrence Berkeley National Laboratory)

Students: John H. Holliman II and J. Kelly Truelove (UC Berkeley)

Abstract

The fragmentation of star-forming molecular clouds is poorly understood, in part because of the highly nonlinear nature of the process and its sensitivity to the initial conditions. Previous simulations of this process have suffered, because the use of more conventional numerical schemes has prohibitive computational requirements and nonrobust treatments of gravity. We have enhanced the stability of our adaptive mesh refinement (AMR) hydrodynamics algorithm, which is coupled to an adaptive solver for gravity. Our work demonstrates that the code is highly discriminating in allocating time resource and can model fragmentation with unprecedented resolution. We obtained results on an emerging test problem that challenges the qualitative outcomes of simulations with identical initial conditions. Possible reasons for the discrepancies are suggested. We also implemented multiple components of pressure support in the code and enhanced our package of visualization tools.

Objectives

Star-formation process plays a crucial role in galactic evolution and is critical in determining the structure of the interstellar medium. Answers to two basic questions concerning this process remain elusive: What dictates the rate of star formation? What determines the relative proportions of low-mass and high-mass stars?

A key step in the star-formation process is fragmentation, whereby massive molecular clouds or clumps within the clouds break up into substantially less massive cores that may condense into stars. In FY 1994, we developed a numerical technology that would allow us to consider this problem realistically. In FY 1995, we shifted our attention to applications. Our ultimate goals were to:

1. Assess the nature of fragmentation in environments where massive stars form.
2. Investigate the sensitivity of the results to the rotational rate, the level of support from Alfvén waves, and the spectrum of density perturbations.

In trying to advance our understanding of star formation, we seek related and more challenging problems with which to test the code.

During this project, a numerical application captured the interest of the computational astrophysics community. At least one group was obtaining radically different solutions in their simulations of a collapse problem originally done by Boss.¹ Results from the latter work, which appeared to show the first numerical evidence for hierarchical fragmentation in molecular cloud cores, were reproduced on the cover of *Nature*. The outcome was embraced by many observers as empirical support for the existence of what may be a common physical process. In addition, the problem has become regarded as a test problem for codes used in hydrodynamic simulations of star-formation processes. Therefore, the deviations seen by other researchers in the results of this simulation were of considerable interest. We adjusted the focus of our efforts slightly to bring the unparalleled efficiency of our AMR algorithm to bear on this problem.

Characteristics of the hierarchical fragmentation problem, as implemented in the most recent work, include an increase in density by 7 orders of magnitude over the course of the run and a large effective resolution that is required to distinguish the fine structures that develop. The recent simulations that prompted our shift in focus used a nested sequence of progressively finer grids, which were present from the onset of the calculation, to reveal the detailed structure that developed. Our code permits an adaptive introduction of refinement that translates into an increase in efficiency and a greater flexibility regarding where we can place the most highly resolved grids.

The high effective resolution required in this study plays to the strengths of the AMR algorithm; however, we found that some adaptation of our code was necessary. The new problem was more demanding, in terms of the dynamic range of cells that had to be introduced, than our proposed investigations into the nature of fragmentation on the larger scale of a molecular cloud clump. Therefore, we increased the robustness of our code, rendering it fully symmetric and stable over the range of conditions that we would simulate. The fact that the revised AMR hydrodynamics algorithm achieves unprecedented accuracy on a standard test suite of problems is encouraging.

The outcome of our simulations calls into question not only the original results published in 1991 but also the claims of ubiquitous fragmentation that came from more recent attempts to reproduce a hierarchical substructure. Like the latter effort, our work revealed a qualitative difference in the collapse: We find that the cloud maintains a density maximum at its center, whereas Boss found a minimum.¹ However, unlike both previous studies, we did not see fragmentation. Our code is more robust in terms of modeling advection across the interfaces of the grids, and it confirmed a weakness in the algorithm used in the latter effort. At least some of the fragments seen in the other work are numerical artifacts that grow from perturbations systematically instigated at the interfaces.

Other progress that we made during FY 1995 includes an augmentation of the code to include the pressure due to nonthermal motions and the impact of transfer effects at high densities on the dynamics of the gas. These issues were neglected in previous studies. Also, we discovered that one of the major challenges in this work is visualizing data that, if rasterized to cover the entire computational domain at the highest level of refinement, occupy more than 0.5 trillion cells. Problems involving the depth of refinement that we used had not been attempted at LLNL. We worked around the

limitations of the existing data-analysis tools to assess the results of our simulations. Also, we requested and received a renewal and an increase in the amount of our allocation of supercomputer time at the Pittsburgh Supercomputing Center.

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Development Work on a Gamma-Ray Burst and Particle Detector for the Mars Surveyor and Pluto Fast Flyby Missions

Principal Investigator: Kevin Hurley (UC Berkeley)

LLNL Collaborator: Klaus Ziock

Abstract

We have built a prototype of a small experiment to measure cosmic gamma-ray bursts and energetic particles. It consists of a cesium iodide-plastic scintillator phosphor coupled to a small photomultiplier tube through a light guide. The analog electronics contains a pulse shape discrimination circuit to distinguish between photon interactions in the CsI and particle interactions in the plastic. This prototype has been delivered for integration on a spacecraft to be launched to Mars in November 1996.

Objectives

Cosmic gamma-ray bursts are one of the outstanding mysteries of twentieth century astrophysics. After 20 years of study, it is still unclear whether they originate from sources within our galaxy or from distant galaxies, representing the most energetic phenomena in the known universe. One approach to resolve the question of their origin is to conduct searches for quiescent counterparts to burst sources in other wavelength ranges, such as the optical or soft x ray. To do this, we needed to have an arcminute or less for locations of bursts. Triangulating the bursts by timing their arrival at three or more widely separated spacecrafts is the only way to accomplish this goal. There is one spacecraft, Ulysses, which is up to 6 astronomical units (AU) in interplanetary space and many spacecrafts in Earth orbit, but there is no planetary mission.

Our goal in this project was to design and build a prototype of a small, low-mass, inexpensive burst detector that can fly on a planetary mission. Our immediate objective was to accommodate it on one of the numerous missions to Mars, which are being built in the United States and Russia. Our long-term goal is to make this experiment attractive enough to include outer planet missions (e.g., to Pluto), which are in the planning phase. This means keeping the mass and power consumption very low and including the possibility of particle detection in addition to gamma-ray burst detection, because it is not known whether planets such as Pluto possess magnetospheres with energetic particle belts.

Progress

We formed a team consisting of four institutions to design this experiment: Lawrence Berkeley National Laboratory and UC Berkeley Space Sciences Laboratory are responsible for the analog electronics and high-voltage design; Lawrence Livermore National Laboratory is responsible for the phototube and crystal assembly and the mechanical design; and Goddard Space Flight Center is responsible for the digital electronics and ground-support equipment. As our design was being carried out, we contacted National Aeronautics and Space Administration and the Institute for Space Research (Moscow) to assess the possible flight opportunities to Mars

for this instrument. A Russian group under the leadership of Igor Mitrofanov agreed to include it as a piggyback experiment for the Mars '96 mission, to be launched in November 1996, with a two-year nominal lifetime.

We proceeded to build and test a prototype of our instrument. We succeeded in reducing the size with respect to previous, similar instruments. Our experiment has a mass of about 700 g, consumes about 550 mW, and has dimensions of approximately 190 mm $\times$ 150 mm $\times$ 75 mm. Laboratory tests of the crystal-phototube-analog electronics chain demonstrate that 15- to 150-keV gamma rays and energetic particles can be distinguished with good efficiency. For example, 1-MeV electrons are identified as particles with 96% efficiency. The unit is also sensitive to protons, although we cannot distinguish between them and electrons. We believe, with further development, the experiment could be made smaller and less massive.

In July 1995, a team of Russian scientists and engineers came to Goddard Space Flight Center for two weeks to test the prototype. After these tests, the unit was taken to Moscow for integration onto the Mars '96 spacecraft. No problems have been encountered. When all aspects of our design have been validated through spacecraft tests, we will proceed to build two flight units. The first will be delivered in November 1996 and will be similar to the prototype. It will consist of approximately 20 cm² of CsI (thickness of 3 mm) surrounded by a 3-mm-thick plastic scintillator, coupled to a Hamamatsu photomultiplier tube. When a gamma-ray burst is detected, we will record it with 16-ms time resolution and measure its energy spectrum over 16 channels.

When this instrument is launched, it will complete the 3rd Interplanetary Network of gamma-ray burst detectors. We anticipate that over its two-year lifetime, it will detect more than 100 gamma-ray bursts, many of which will be localized by triangulation to arcminute or better. This will enable radio, infrared, optical, and x-ray observations of unprecedented sensitivity to be carried out, in an effort to solve this 20-year-old mystery.

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The Evolution of Supermassive Objects

Principal Investigator: George M. Fuller (UC San Diego)

LLNL Collaborators: James R. Wilson, Thomas A. Weaver, and Karsten Jedamzik

Student: Gail C. McLaughlin (UC San Diego)

Abstract

We have studied aspects of the general relativistic instability of supermassive stars (with mass $M \geq 10^5 M_\odot$). In particular, we found that the onset of this dynamic instability can be delayed through the hydrogen-burning main sequence phase when a significant nonrelativistic component of dark-matter particles is in such a star. In turn, this delay could allow the nucleosynthesis products of hot hydrogen burning to be ejected in winds prior to the collapse of the star to a black hole.

Also, we examined the prospects of such objects forming in the early universe in the context of baryon isocurvature models for structure formation. We computed the expected primordial nucleosynthesis yields in baryon isocurvature models with significant nonlinear fluctuations on small mass scales ($M \geq 10^{12} M_\odot$). Interestingly, our calculations show that, for some isocurvature models, the deuterium yield can be significantly enhanced over that in standard big bang nucleosynthesis scenarios.

Objectives

Our objectives for this project involved studying issues related to the formation, evolution, and nucleosynthesis of massive and supermassive stars and black holes. In particular, we wanted to examine: (1) the physics of the post-Newtonian instability in the presence of a dissipationless component of nonrelativistic dark-matter particles (e.g., massive neutrinos, or neutralinos); (2) the nucleosynthesis from the collapse and (possibly) subsequent thermonuclear explosion of supermassive stars; (3) the role of angular momentum in setting the mass and initial composition boundary between collapse to a black hole and thermonuclear explosion; (4) primordial nucleosynthesis in the inhomogeneous environment engendered in baryon isocurvature models; and (5) the production and formation of condensed objects in baryon isocurvature models. We also wanted to elucidate the role of the radiation background in the cooling and collapse of fluctuations, as part of our study of condensed objects.

Progress

In FY 1995, we made considerable progress on several of these goals. We analyzed the post-Newtonian instability in a supermassive star, which we have taken to be imbedded in a halo of dissipationless dark-matter particles (we assumed that the dark-matter particles have only gravitational interactions). Our numerical calculations show that the presence of the non-relativistic component can lead to enhanced stability. We computed the fractional mass-energy contribution of dark matter required to stabilize the supermassive star through hydrogen burning. In general, we concluded that the required dark-matter density is too large to have arisen in objects forming in the early universe. However, supermassive stars formed from stellar mergers and tidal disruptions in galactic cores may be progenitors of the large black holes believed to power quasars and active galaxies. It is not inconceivable that supermassive stars could acquire a significant dark-

matter component in such formation scenarios. In any case, the post-Newtonian instability can only be postponed. A stable hydrogen-burning phase for these stars guarantees that they will collapse to black holes. We also estimated the amount ($\sim 10^3 M_{\odot}$) and the abundance pattern of the hot hydrogen-burning products that could be ejected in a wind in a putative stabilized main sequence phase for a supermassive star.¹

In future work, we plan to modify the KEPLER code to study the nucleosynthesis expected from stabilized supermassive star ejecta. We also plan to examine the evolution and nucleosynthesis from rapidly rotating supermassive objects with a modified version of J. Wilson's code.

We made considerable progress on computing the evolution of objects and fluctuations and the associated primordial nucleosynthesis in baryon isocurvature models for structure formation. These models have not been ruled out by microwave background anisotropy constraints. Also, they remain a viable alternative to the standard structure formation models, which invoke gravitational growth of (initially) linear regime fluctuations with an initial Harrison–Zeldovich power spectrum. When we examined the primordial nucleosynthesis that would emerge from broad classes of baryon isocurvature scenarios, we found that the models were inconsistent with observationally derived constraints on light-element abundances, unless a small mass scale cutoff in power was introduced. Whether such a cutoff can arise naturally from some fluctuation production process in the early universe is an open question. However, when such a cutoff is present, our calculations show that the light-element nucleosynthesis yields are acceptable.

We also found that these models tend to enhance the production of deuterium over standard big bang nucleosynthesis models.² This enhancement may become significant, especially if the tentative claims for high deuterium-to-hydrogen ratios derived from observations of Lyman- α clouds hold up.

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Unified Models and the Alignment Effect in Radio Galaxies

Principal Investigator: Robert Antonucci (UC Santa Barbara)

LLNL Collaborators: Wil van Breugel and Andrea Cimatti

Students: Todd Hurt (UC Santa Barbara) and Arjun Dey (UC Berkeley)

Abstract

Using the Lick Observatory telescope, the UC–Caltech Keck telescope, and the Hubble Space Telescope (HST), we have been making observations related to the Alignment Effect in high-redshift radio galaxies and the Unified Model for active galactic nuclei and quasars. Also, we have searched for active objects at higher redshifts. The observations from the Lick Observatory and Keck telescopes revealed hidden quasars in radio galaxies and infrared sources at low- and high-redshifts and a surprising nonconfirmation of polarization in the prototypical aligned high-redshift radio galaxy 3C368. Also, from the Lick Observatory, a $z = 3.54$ radio galaxy, the first radio-loud broad absorption line object, was discovered.

Objectives

Our goal was to use the polarization observations to determine the meaning of the Alignment Effect and the implications of the active galaxy Unified Model. We also used these observations to search for new active objects at higher redshifts.

Progress

In this collaboration, we found evidence for a hidden quasar in the radio galaxy Coma A, which was one of the results from the Lick Observatory polarization survey of nearby infrared-loud radio galaxies. We also made two successful runs with the Keck telescope dedicated to spectropolarimetry of high-redshift aligned radio galaxies. Data from these runs indicate hidden quasars in many objects.^{1,2} In addition, we found nonconfirmation of high polarization in the prototypical aligned radio galaxy 3C368. This observation, with HST polarization imaging, shows that intrinsic emission must play a role in the alignment phenomenon.

Also, we have been investigating samples of radio sources to find high-redshift quasars and radio galaxies. Chambers et al. showed a correlation between radio spectral index (α) and redshift (z) for Jansky-level radio sources.³ Since this α – z correlation provides a method for selecting high- z objects, we have been observing samples of faint ($S_{20\text{ cm}} \sim 10\text{--}100\text{ mJy}$), ultrasteep spectrum ($\alpha < -1$, $S_\nu \propto \nu^\alpha$) radio sources. In FY 1995, we cross-correlated the 7C survey at 151 MHz (Ref. 4) with the first data from the Very Large Array FIRST survey at 11,490 MHz (Ref. 5), to produce a sensitive sample of faint, ultrasteep spectrum (USS) radio sources. After defining the sample, we used optical imaging to search for source identifications. Then follow-up spectroscopy can be used to provide the redshift. The spectroscopy is aided by some high- z radio galaxies exhibiting strong emission lines; some contain Ly- α lines with observed equivalent widths $\geq 1000\text{ \AA}$ ⁴ (Ref. 6).

In April 1995, we took deep optical images of about 15 radio fields with the Lick 3-m telescope. In August 1995, with observations of a brighter sample of USS sources, we discovered a radio galaxy (1909+72), at $z = 3.54$. In 1996, we will continue our observations of the radio samples,

including spectroscopy of identified objects to determine redshifts. At the Keck telescope, subsequent observations by have shown that 1909+72 is a radio galaxy with a broad absorption line (BAL) system. This is the first radio-loud BAL known. The BAL in 1909+72 could result from absorbing gas near the active galactic nuclei (as in BAL quasars)⁷ or outflows from massive stars. In addition, our Lick image shows evidence for rest-frame ultraviolet emission extended along the radio axis. Object 1909+72 may be another example of the high- z alignment effect. For these reasons, we will include it in our program of Keck spectropolarimetry of radio galaxies. The polarization properties of the BALs will provide information on the unresolved geometry of these sources,^{8,9} and spectropolarimetry of the extended emission will determine whether it is in situ emission or scattered from a hidden quasar.

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Shock Synthesis of Amorphous Fayalite

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LLNL Collaborator: William J. Nellis

Student: Abby Kavner (UC Berkeley)

Fayalite, the iron end-member of olivine, is observed to undergo a crystalline to amorphous phase transformation in the diamond-anvil cell. Fayalite powder recovered from shock experiments shows evidence of glass quenched from the melt, but not the expected diaplectic glass. Here, we explore the kinetic regimes under which amorphous fayalite is synthesized by shocking single-crystal fayalite under different conditions.

Abstract

Phase transformations of olivine dominate the chemistry of the Earth's transition zone. The details of how these transformations occur affect the convection in the upper mantle, the fate of subducted slabs, and possibly the mechanism of deep focus earthquakes. The two experimental methods we have of accessing these pressures, statically in the diamond-anvil cell and dynamically via shock apparatus, usually yield compatible results and thus are important cross-checks of high-pressure experiments. For fayalite, the iron end-member of olivine, the high-pressure phase transformation seems to be extremely path dependent. Metastable static compression at room temperature yields an amorphous phase at pressures above 40 GPa in the diamond-anvil cell,¹ yet no quenchable phase transformation under shock loading, except for a quenched melt glass after shocking powder compacts.²

The objective of the study was to use the shock-wave facilities at LLNL as a tool to explore the shock kinetic regime necessary to synthesize amorphous fayalite. Comparing results from the two high-pressure techniques, diamond-anvil cell and shock experiments, allows us to probe directly the kinetics of phase transformations. Furthermore, shock compression is directly relevant to understanding the appearance of rare high-pressure phases (ringwoodite and majorite) in certain chondritic meteorites.

Objectives

High-pressure shock experiments were performed on three single crystal disks of synthetic, high-purity fayalite. The first experiment was performed on a disk of fayalite precooled to liquid nitrogen temperatures and shocked to 63.5 GPa, more than 50% above the pressure at which fayalite amorphizes in the diamond cell. The second fayalite disk was also shocked to 63.5 GPa but was not precooled. The third fayalite sample was shocked in an impedance-matched titanium alloy target. Using this target allowed a maximum pressure of 75 GPa to be reached in a single shock, instead of the slower "ringing up" in pressure experienced by the fayalite in the normal stainless-steel capsule. This third sample was also precooled.

The recovered material was examined by x-ray diffraction, transmission electron microscopy (TEM), and optical microscopy and reflectance Fourier transform infrared (FTIR) spectroscopy of prepared thin sections. The x-ray diffraction showed a complete fayalite diffraction pattern with no extra or

Progress

missing peaks and no evidence of an amorphous background. The recovered samples were very highly strained, with optical microstructures closely resembling previous work on shock-recovered, highly dislocated olivines.³ The recovered fayalite samples retained their single crystal character and showed no evidence of recrystallization. The samples were extremely beam-sensitive in the TEM, but even with cold-stage microscopy in which the sample is cooled to liquid nitrogen temperatures, there was no evidence of glass seen under the TEM.

This is the first example of a phase transformation that clearly does not show a correspondence between the diamond cell and shock processing. Therefore, we are directly probing the kinetics of the olivine–spinel–amorphous fayalite reaction. This correspondence between kinetic regime and phase allows us to map out expected olivine microstructures for different regimes of pressures and temperatures, allowing olivine to be a tracer mineral for the pressure–temperature histories of impacts or of more nearly uniform pressure environments.

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Seebeck Coefficient and Quantitative Electrical Conductivity Models for Olivine Rock

Principal Investigator: Steven Constable (UC San Diego)

LLNL Collaborator: Alfred G. Duba

Abstract

Our studies of a dunite and lherzolite, both olivine-rich rocks, suggest that their electrical conductivity is dominated by olivine, a result that is in marked contrast to the accepted models extant when we began our IGPP collaboration. This olivine dominance is indicated by conductivity-temperature and conductivity-oxygen fugacity (fO_2) behavior, as well as qualitatively similar Seebeck coefficient (thermopower). It suggests that the small polaron is the dominant charge carrier in the rocks. Thermopower determines the sign and concentration of the dominant charge carrier as the result of the migration of the conducting species from the hotter electrode of a sample in a temperature gradient. However, at least two conducting defect species must be invoked to explain the observed magnitude and fO_2 dependence of thermopower, and both electron/polaron and polaron/magnesium vacancy conduction can be made to fit the conductivity and thermopower data if a constant polaron or magnesium vacancy term is included (or a $1/11$ power dependence of defect population taken). However, to model the small magnitude of the thermopower requires unrealistically high concentrations of polarons. Grain-boundary conduction may be responsible, since thermopower does appear to decrease with decreasing grain size. Fits with reasonable defect concentrations can be obtained if the thermopower is arbitrarily scaled.

Objectives

An understanding of defect chemistry is important in the study of the electrical conductivity of Earth's mantle. Currently, it is difficult to measure the electrical conductivity of mantle materials under simultaneously controlled conditions of pressure, temperature, oxygen fugacity, water activity, silica activity, and iron activity. A thorough understanding of the point-defect mechanisms that determine conductivity in olivine rocks will help us extrapolate measurements to conditions applicable to the mantle. Because silicates are insulators or, at best, poor semiconductors, their electrical conductivity depends strongly on the defect population. Also, because electrical measurements are relatively straightforward, we can easily monitor with high accuracy how variations in environmental parameters affect the defect population. To sort among possible mechanisms that could be responsible for conduction in olivine at any given temperature, we use the defect model of Hirsch and Shankland,¹ our measurements of diffusion, and our measurement of the sign and oxygen fugacity dependence of thermoelectric power.

Progress

The rock used in this study is a lherzolite from Mount Porndon, Australia, with an approximate modal composition of 3% clinopyroxene, 31% orthopyroxene, 1% spinel, and 65% olivine and a grain size of about 1 mm. Electrical conductivity and thermopower were measured in an apparatus that is described in detail by Duba et al.² Oxygen fugacity is controlled by a metered flow of CO and CO₂ through the apparatus, and electrical conductivity measured as a function of oxygen fugacity exhibits approximately a

1/11 power dependence. Thermopower was determined using the method described by Schock et al.³

Tuller and Nowick⁴ provide an expression for thermoelectric power of polaron hopping based on the entropy transported by the charge carriers. Their expression can easily be inverted to obtain an expression for polaron concentration given thermopower. Thermoelectric power is thus predicted to decrease with increasing oxidation state, in marked contrast to the observed increase of thermopower with $f\text{O}_2$ at fixed temperature. Also, the magnitude of the thermopower is inconsistent with the reasonable defect concentrations. This suggests a different conduction mechanism or mixed conduction. Several workers have proposed mixed electron and polaron conduction in olivine. For example, Hirsch and Shankland¹ modeled an effective charge-carrier population of electrons, polarons, and magnesium vacancies. However, we assume that polarons are responsible for the positive thermoelectric power because the only other positive charge carriers are cation interstitials of low abundance. For mixed conduction, total thermoelectric power is given by the thermopowers of the individual charge carriers weighted by the contribution to the total conductivity. Thus, for example, an increasing contribution of polaron conduction with increasing $f\text{O}_2$ might well account for the positive slope of the thermopower- $f\text{O}_2$ relationship.

We developed a quantitative model of mixed-conduction thermopower and used a parameter inversion scheme to recover concentrations and mobilities of various defect combinations, which fit the observed data of conductivity and thermopower as a function of $f\text{O}_2$. Although we do not claim to have searched all of model space, about 100 inversions were run from different starting models and with various constraints on model parameters. We discover from our modeling that, even with concentrations and mobilities for three defect species as free parameters, we are not able to fit the conductivity data well if we assume the 1/5.5 power dependence of concentration on $f\text{O}_2$ modeled by Hirsch and Shankland. We must include a constant term in the polaron concentration to fit the conductivity data well, as noted by Duba and Constable.⁵

The following observations are made based on our inversions:

1. The concentration of polarons is too high in all models that fit the data, with values of 10% of total iron content typical. Efforts to force this parameter to lower values degrade the fit severely.
2. Inversions in which magnesium vacancy concentration is forced to zero fit the data well with plausible values of electron mobility and concentration. The thermopower plunges steeply at low $f\text{O}_2$, but this decrease is not constrained by data and is not necessarily an intrinsic property of the model.
3. Inversions in which electron concentration is forced to zero fit the data with magnesium vacancy concentrations about an order of magnitude higher than those used in the Hirsch and Shankland models,¹ but the more serious problem is that magnesium vacancy mobility is comparable to polaron mobility. The interesting behavior in these inversions is that the constant magnesium vacancy term dominates the $f\text{O}_2$ -dependent term, and the $f\text{O}_2$ -dependent term can easily be forced to zero without degrading the fit. This behavior, in fact, is what is plotted Figure 1. Almost identical results can be obtained using a constant electron term and no magnesium vacancies. The flattening at high $f\text{O}_2$ is similar to that seen in the Wanamaker⁶ data.

The presence of constant terms in the defect parameterization is required to change the expected slope of $1/5.5$ into about $1/11$, so we might well ask what the behavior of our inversions would exhibit if a $1/11$ power is used in the modeling instead. Apart from the consistently lower slopes of the conductivity- $f\text{O}_2$ data, pyroxene buffering lowers the magnesium vacancy dependence in Hirsch and Shankland's models, providing some justification in lowering the power of the $f\text{O}_2$ dependence. Indeed, a $1/11$ dependence allows us to fit the data in a manner similar to that described above, but without including a constant term. While our modeling demonstrates that mixed conduction can explain the behavior of both conductivity and thermopower, we have the problem that the polaron concentration and mobility of magnesium vacancies are both too large, although mixed polaron/electron models produce reasonable values for both electron concentration and mobility. That the models favor a constant population of magnesium vacancies, rather than a strongly $f\text{O}_2$ -dependent one, is not inconsistent with the effect of pyroxene buffering in Hirsch and Shankland's models¹ but could also be associated with a population of magnesium vacancies frozen in from higher temperature during the sample's history in both the Earth and the laboratory.

Figure 1. (a) Electrical conductivity data and (b) thermopower data with model fits as described in the text. The solid line is for a model consisting of a two-component polaron contribution and a constant concentration of either magnesium vacancies or electrons. The dashed line is for a model with $1/11$ and $-1/11$ dependences for polarons and magnesium vacancies, respectively.

Even with mixed conduction, the cost of lowering the thermoelectric power seems to be an increased concentration of polarons. There are various reasons why our thermopower modeling could be inadequate: Vibrational entropy for polaron transport may not be negligible as assumed, the spin degeneracy factor may not be 2 as assumed, and the effective mass of electronic conduction may be higher than the electron mass. However, it is unlikely that any of these factors would be enough to drop the polaron concentration by 2 orders of magnitude. Rather, we must look for some mechanism that would reduce the magnitude of the observed thermopower, and once again, the effect of grain boundaries may be important.

Examination of the literature shows that thermopower decreases with decreasing grain size; the dunite of Roberts and Duba,⁷ with a grain size of about 0.3 mm, is finer than the lherzolite, which is finer than the single crystal. Grain size can have a profound effect on thermopower; Chatterjee et al.⁸ observed an n-to-p transition in galena as grain size decreased from 110 to 60 μm . We have assumed that the various conduction mechanisms operate in parallel, but if surface conduction is important, there will also be a series contribution to thermopower. Although we lose the objectivity applied to the modeling above, by arbitrarily reducing the size of the polaron thermopower to one-third, we can fit the morphology of the conductivity and thermopower data with models that have defect concentrations comparable to those of Hirsch and Shankland's models.

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Equations of State of Planetary Materials by X-Ray Diffraction at High Pressures and Temperatures Achieved by Laser Heating

Principal Investigators: Malcolm F. Nicol, Hyunhae Cynn, and Diane Reifschneider (UC Los Angeles)

LLNL Investigators: Choong-Shik Yoo and Jagan Akella

Abstract

This project combined experience with laser heating and x-ray diffraction studies at high pressures to study phase relations in iron and alumina and reactions among light elements leading to new hard materials in situ at high pressures and temperatures. We developed new x-ray collimators, image plate detectors, and laser heating technology for diamond-anvil cells for experiments done at the Stanford Synchrotron Radiation Laboratory and other synchrotron sources.

Objectives

The scientific basis of this project is measuring in situ, at high pressures and temperatures, structures, equations of state, and chemical reactions among materials that compose, or serve as a model for, the interiors of the Earth, other planets, their satellites, and comets. The cores of the Earth and terrestrial planets are thought to contain a large proportion of Fe with significant amounts of Ni, O, S, Si, and other elements. More primitive planets, their satellites, and comets should consist of dense, often hot, mixtures of relatively simple molecules. Pressure–volume–temperature (P - V - T) equations of state and chemical reactivities of iron, iron alloys, and mixtures of simple molecules at high pressures and temperatures are needed to model the interiors of these bodies. Laboratory measurements of these properties at high static pressures and temperatures would be useful for constraining models of planetary interiors. The thrust of this work is to show that such accurate P - V - T , phase, and chemical equilibrium data can be collected at static high pressures and temperatures for these materials.

Progress

Over the past few years, we developed the laser heating technique and powder x-ray diffraction methods with a synchrotron source and image-plate detectors for diamond-anvil high-pressure cells. In FY 1995, we combined and improved these techniques to make measurements at the wiggler beam line of the University of California–National Laboratories Participating Research Team (PRT) at the Stanford Synchrotron Radiation Laboratory (SSRL). With the help of David Schiferl and Robert Martinez of Los Alamos National Laboratory, we installed a new image plate camera and x-ray microcollimator that were much easier to use and to align to high-pressure cells. These components are being shared with other groups in the PRT.

We also installed a new setup for x-ray diffraction during laser heating with diamond-anvil cells at the PRT beam line. The three major components of this system are a neodymium:yttrium-aluminum-garnet (Nd:YAG) laser for heating the samples, a microscope-spectrometer system for aligning and viewing the sample and for measuring temperatures during laser heating, and the synchrotron x-ray source with microcollimators and angle-resolved

image-plate detection. In a typical experiment, a small piece of a thin iron foil is loaded in a diamond anvil cell with a pressure medium such as N_2 , H_2 , Ar, LiF, Al_2O_3 , or MgO. The output from the Nd:YAG laser is focused on the iron and heats it because iron absorbs 1.06- μm radiation from the laser much more strongly than diamond or these pressure media do. By aligning the hot spot created by the laser on the part of the sample exposed to x rays, we can collect angularly resolved diffraction patterns on the image plates from the hot sample. The temperature of the sample is detected by measuring the thermal emission from the area heated by the laser, and the pressure is measured either from the x-ray pattern and known equation of state or by the ruby luminescence method. With current technology, x-ray diffraction studies are feasible at pressures above 100 GPa and temperatures of several thousand kelvins. Because the amount of beam time to each PRT user is limited, some measurements described here were made by taking the equipment to other synchrotron sources.

We used these techniques to study the phase diagram of iron to 130 GPa and 3500 K and made the first direct identification of the phases at high pressures and temperatures, including the phases that melt under pressure. The γ - ϵ -fluid triple point was located at 2500 (± 200) K and 50 (± 10) GPa. No evidence was found for either β -Fe or the proposed α -Fe to at least 110 GPa. Evidence for a new phase was obtained above 110 GPa and 3000 K, and a new ϵ' (dhcp) phase was detected at lower pressures.

Pressure increases the thermodynamic stabilities of dense materials and may increase rates of chemical reactions leading to these products. Examples include the dense mineral phases of the deep mantle and production of hard materials with (1) three-dimensional covalent networks from the light elements, such as diamond, cubic boron nitride, other carbides, and nitrides; (2) oxides from molecules with strong covalent bonds, such as nitrogen; and (3) oxygen or solids held together by van der Waals forces, such as boron and graphite. High activation barriers often prevent these reactions from initiating. A natural solution to this problem is to heat the compressed material and search for products by the appearance of new features in the diffraction patterns from the hot zone. These dense products are typically metastable at low temperatures because the activation barriers also are high for the reverse reactions; therefore, the products often can be quenched and recovered at ambient conditions.

In this project, we took a direct synthetic route to nitrides of boron and silicon by reacting the very inert molecular nitrogen directly with elemental boron and silicon in the laser-heated hot zone. The products were identified in situ by x-ray diffraction. The fact that we produced β - Si_3N_4 directly from silicon and N_2 is especially interesting. It has been suggested on theoretical grounds that the carbon analog of the same structure, β - C_3N_4 , might be an especially hard material. The success of the silicon–nitrogen reaction suggests several pathways for producing this material that we are exploring. This line of research also will be extended to other elements and beyond binary compounds.

New features have been detected in x-ray diffraction patterns of samples of Al_2O_3 subjected to high-pressure shocks. We are analyzing these patterns and attempting to obtain vibrational spectra of the recovered material that might help to identify the new component produced by shock compression.

Optical Absorption and Reflectance Measurements of Iron Sulfides at High Pressure: Application to the Nature of Bonding in Earth's Outer Core

Principal Investigator: Elise Knittle (UC Santa Cruz)

LLNL Collaborator: Robin Reichlin

Students: Jessica Faust and Phillip Cervantes (UC Santa Cruz)

Abstract

We have measured optical absorption spectra of FeS₂ (pyrite) to pressures of approximately 20 GPa through the diamond-anvil cell. Our data show a strong pressure shift of the absorption edge of 0.03 ($\pm$ 0.002) eV/GPa and predict that metallization of FeS₂ will occur near 36 GPa. Reflectance spectroscopy and absorption measurements on FeS₂-pyrite at higher pressures are in progress to augment our work. The nature of bonding between iron and the light-alloying components of Earth's outer core is likely to control the physical properties and nature of phase relations of the outer core; therefore, we anticipate that our data on the high-pressure electronic structure of pyrite will be important in providing first-order constraints on the high-pressure bonding properties in the iron-sulfur system.

Objectives

The observation that Earth's magnetic field is generated within the liquid outer core demonstrates that the core fluid is also an electrical conductor. Therefore, the nature of the bonding between iron and the primary light-alloying component of the core should be compatible with the existence of an electrically conducting, iron-rich fluid. Moreover, the bonding present between iron and the lighter-alloying component is likely to modulate the thermochemistry of dissolution of core material and thus is important in determining the phase relations of the core liquid. However, the role of sulfur in determining the nature of the bonding in core fluid is largely unexplored. Indeed, the first-order question of whether sulfur continues to bind stably at high pressures in S₂²⁻-dimers, as in FeS₂-pyrite at low pressures, or behaves more similarly to oxygen, as in FeS-troilite, remains unknown.

Our goal is to investigate the bonding properties of iron sulfide at high pressures by constraining its high-pressure electronic structure. Our experiments are designed to elucidate the nature of iron-sulfur bonding at high pressure to gain insight into the bonding of the light-alloying components in the Earth's core. Specifically, we expect to determine at what pressure pyrite becomes metallic and to clarify the high-pressure stability of sulfur-sulfur bonding in this sulfide. Additionally, the high-pressure properties of sulfides are interesting from both a theoretical and the crystal-chemical configuration. Thus, we have characterized the electronic (optical) absorption and reflectance spectra of FeS₂ (pyrite) at high pressures using the diamond cell. These spectroscopic techniques provide a direct method of obtaining information on the electronic structure of materials at high pressures and are particularly sensitive to the nature of their chemical bonds. For example, the optical absorption and reflectance spectra can be straightforwardly used to determine whether FeS₂ becomes metallic at high pressure or whether it remains semiconducting.

Progress

We have measured the optical absorption spectra of FeS_2 -pyrite to pressures of nearly 20 GPa through the diamond-anvil cell (Figure 1). Because of the high opacity of pyrite, these measurements are not routine and are essentially measurements of a thin film of this material. At ambient conditions, the bandgap (absorption edge) for our sample of pyrite is $0.98 (\pm 0.5)$ eV: This energy corresponds to the transition between the t_{2g} orbitals of iron (bonding states) and the e_g^* energy band resulting from overlap of iron–sulfur–iron e_g symmetry nonbonding orbitals. We observe that the bandgap of pyrite decreases monotonically with pressure with a shift of $0.03 (\pm 0.002)$ eV/GPa. This result is in contrast to previous work where a small increase in the bandgap of pyrite is observed to pressures of 4.2 GPa based on optical reflectance spectra.¹ A linear extrapolation of our results predicts that FeS_2 should metallize at a pressure of 36 GPa. Interestingly, high-pressure x-ray diffraction and shock-wave measurements indicate that pyrite does not undergo a significant structural phase transformation to pressures of 320 GPa.^{2,3} Our data thus indicate that metallization of pyrite is not accompanied by a first-order structural phase transformation and is likely to be nearly isovolumetric.

Optical absorption and reflectance measurements to higher pressures on pyrite are in progress. Reflectance measurements of pyrite through the diamond cell should provide a particularly robust test of our prediction of metallization based on the lower-pressure bandgap data. If, as expected, metallization of pyrite does occur under these comparatively modest pressure conditions, then the apparent stability of pyrite to ultrahigh pressures demonstrated by the shock-wave results implies that sulfur dimers could represent the predominant sulfur species within the outer core of Earth.

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Figure 1. Bandgap energy versus pressure for FeS_2 pyrite measured through the diamond cell. A linear extrapolation of the data predicts metallization of pyrite at 36 GPa.

Quaternary Differential Rates of Uplift in the Northwestern Himalaya Using Cosmogenic Nuclide Dating of Strath Terraces

Principal Investigator: Mary R. Reid (UC Los Angeles)

LLNL Collaborators: Robert C. Finkel and Marc Caffee

Student: John Leland (UC Los Angeles)

Abstract

We determined cosmogenic ^{26}Al and ^{10}Be exposure ages for river-cut bedrock terraces abandoned by the Indus River in a region in northern Pakistan undergoing apparent differential uplift. The exposure ages yield incision rates that show a pattern of increasing incision downstream in the study area over the past 65,000 years. The pattern of incision supports the hypothesis that the Indus River responds to downstream uplift by increasing incision through its bedrock channel and that the apparent differential uplift inferred from previous fission track studies is real.

Objectives

Streams interact with the landscape through a complex system of feedbacks involving climate, topography, and tectonics. Understanding and quantifying the relationships between the elements in this system have been major goals in geology for many decades. Until recently, few studies had been able to quantify the rates at which streams incise their bedrock channels. Knowledge of bedrock incision rates was sought to better understand the magnitude of a stream's ability to contribute to denudation of the landscape and respond to external tectonic forcing.

This study has quantified bedrock incision rates along the Indus River in northern Pakistan. In the study area, between the Skardu Basin and the Gilgit–Indus confluence (Figures 1a and 1b), the river flows across bedrock that exhibits a gradient in apatite and zircon fission track ages, which implies differential uplift along the river's course. Bedrock benches (straths) cut and abandoned by the river remain well-preserved and were our targets for ^{10}Be and ^{26}Al exposure age dating. The abandoned straths record the river's level with respect to surrounding bedrock and the modern river channel and, when dated, yield information on incision rates and paleogradients. Once patterns of incision within the study area are established, we can model uplift rates based on differential incision rates and compare them to longer-term denudation rates calculated from previously published apatite and zircon fission track ages.

Progress

Our field observations led us to conclude that the sampled strath surfaces had experienced little erosion. Using a single isotope erosion model, we calculated that the erosion rate on the highest strath yet dated in the study area can be no more than 8 m/Ma, corroborating our field observations. Because this surface is in an excellent state of preservation, it is unlikely that erosion has significantly affected its cosmogenic exposure age or any of the other well-preserved surfaces sampled in the study area. Several samples do yield $^{26}\text{Al}/^{10}\text{Be}$ at the production value, and all but two samples overlap the production value of $^{26}\text{Al}/^{10}\text{Be}$ at the 2- σ level.¹ The cosmogenic signal

Figure 1. (a) Overview map of the study area, which is between the Skardu Basin and the Gilgit-Indus confluence. (b) Detailed map of the study area, showing the sedimentary profile. (c) Relationship of the strath locations, height above the Indus River, and cosmogenic exposure ages.

inherited during strath cutting prior to abandonment by the river is less than 3000 years.

Figures 1b and 1c show the relationship between strath location, height above the Indus River, and cosmogenic exposure age. Exposure ages increase with elevation above the river at any locality along the river, consistent with progressive formation of the terraces by river downcutting. However, comparing straths at similar heights above the Indus River yields interesting results. Two high straths between 140 and 160 m above the Indus River near the Skardu Basin yield exposure ages between 60,000 and 65,000 years, yet further downstream a similarly high strath at 155 m above the Indus River yields an age of 27,000 years. Bedrock incision rates calculated from these strath ages range from 2.3 m/1000 years upstream to 5.6 m/1000 years downstream, reflecting a twofold increase in incision rates downstream. The downstream increase in incision rates mimics the downstream increase in denudation rates calculated from apatite and zircon fission track ages² in both location along the river and magnitude.

The ages from the lower straths tell a slightly different story. All lower straths have exposure ages of less than 10,000 years. From these younger, lower straths, we calculate incision rates that increase from 8.8 m/1000 years near the Skardu Basin to 13.6 m/1000 years downstream. These incision rates follow the trend described by the older surfaces of about a twofold increase in incision rates downstream, but at rates that appear to have at least doubled over the past 10,000 years.

Differential uplift rates modeled on these strath ages show that the downstream portion of the Indus has been uplifting 2 to 6 m/1000 years faster than the upstream portion near the Skardu Basin over the last 60,000 years. This seems to imply an acceleration in uplift rates in the late Pleistocene when compared to denudation rates based on apatite and zircon fission track ages. However, when we consider the change in incision rates observed between younger (<10,000 years) and older (27,000 to 65,000 years) straths, the modeled acceleration in uplift rates could in fact be caused in part by late Pleistocene, climatically induced peaks in the Indus River's stream power.

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Numerical Simulations of Convergent Crustal Plateau Formation and Mantle Dynamics with Regard to Tibet

Principal Investigator: William M. Kaula (UC Los Angeles)

LLNL Collaborator: Charles Williams

Other Collaborators: Adrian Lenardic (UC Los Angeles) and Louis N. Moresi (California Institute of Technology)

Abstract

We have developed first-generation models of coupled crustal deformation and mantle convection to examine how convergent crustal plateau formation in Tibet may affect, and be affected by, local convective flow in the mantle below. The models broadly outlined possible modes of crust–mantle interaction and demonstrated how, under geologically reasonable conditions, the formation of a convergent crustal plateau could induce a convective instability in the mantle below. Model results removed theoretical objections to the idea that a large portion of the lithosphere below Tibet could have been rapidly removed via a convective mantle instability, as some indirect lines of observational evidence suggest it was.

The initial models further showed how such a delamination type event could account for the delayed onset of extension within the Tibetan Plateau and the lack of a seismic high-velocity lid below portions of it. Significant time was dedicated to modifying the models to allow for the multi-rheologic nature of the Earth's lithosphere and to extend them to three dimensions. The more advanced models are being used to verify the robustness of earlier results and thus help provide added insight into the mechanism behind the most recent phase of uplift in Tibet.

Objectives

Observational evidence suggests that the initial phase of plateau formation in Tibet induced a convective instability in the mantle lithosphere, which affected subsequent evolution of the plateau itself. Physical understanding of this process, in which lithospheric deformation alters local mantle convection patterns, which then feed back and affect subsequent lithospheric deformation, is limited. Few dynamic models have treated compressional lithospheric deformation and local convective mantle flow as truly coupled problems, despite evidence, most clearly documented for Tibet, that they may well be. This oversight has, in part, led to some debate in regard to the driving mechanism behind the most recent phase of uplift in Tibet. Therefore, it was our intent to develop and explore the implications of numerical models that coupled lithospheric compression and accompanying crustal thickening to local convective flow in the mantle. Model outputs, such as the timing of the onset of extension within a plateau region, would be compared to observational data to help constrain physical processes capable of accounting for the geodynamic evolution of the Tibetan Plateau, with emphasis on its most recent geologic history.

Progress

Documented models to date were used to map out potential modes of crust-mantle interaction in zones of convergent crustal plateau formation.¹ Two end-member cases representing either a uniformly strong or a uniformly weak mantle lithosphere were consistent with previous studies related to convective mantle instability below Tibet: (1) A strong lithosphere remained convectively stable, which implied that uplift of Tibet as a result of rapid removal of a mantle root would be unlikely. (2) A weak lithosphere allowed for rapid removal at the expense of using the unlikely condition that the lithosphere has little added strength relative to the bulk mantle. Results from either end-member case were not fully consistent with geophysical data related to Tibet or with inferences based on that data. A third, previously unexplored, mode, which required a strong mantle lithosphere that could develop regions of local weakness, showed the most interesting behavior. Once local weakness developed, an instability akin to delamination could develop in the strong portion of the lithosphere below a crustal plateau. This third case occurred within a geologically reasonable parameter regime and produced results more consistent with geophysical data than did the other cases.

Additional modeling insight into Tibetan geodynamics required us to further develop our models to include, in a more realistic manner, brittle behavior in the cold portions of the Earth's lithosphere. Allowing for brittle behavior is key because it determines the absolute value of near-surface stresses, which, as well as being key on their own, are used to calculate model topography that can then be compared to data. To include the multi-rheologic nature of the lithosphere, techniques developed for critical taper-wedge modeling were incorporated into our convection models. Initial results suggest that brittle behavior can enhance the tendency for local zones of weakness to form in the lithosphere allowing delamination-type instabilities to occur under a wider range of parameter conditions. Further modeling and comparisons of model outputs to data are under way.

The last major progress made during FY 1995 was to adapt a three-dimensional (3D) convection code, developed at the California Institute of Technology, to problems of crustal deformation and local mantle convection. Initial results show that convective instability in the mantle lithosphere below a region of thickened crust can take on spatial variations that lead to different local modes of compensation across a crustal plateau or a mountain belt. Although preliminary, this finding suggests that gravity and topography variations across Tibet can potentially indicate whether mantle lithosphere has locally detached as a result of a crustal-thickening-induced instability. The 3D models at this stage do not have the rheologic complexity of the 2D models, but we are now working to combine rheologic and geometric realism.

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Crustal Thickening in Southern Tibet: The Renbu Zedong Thrust

Principal Investigators: T. Mark Harrison and An Yin (UC Los Angeles)
LLNL Collaborator: Frederick J. Ryerson

Abstract

Inverse modeling of the $^{40}\text{Ar}/^{39}\text{Ar}$ results from a transect across the trace of Renbu Zedong Thrust (RZT), southeastern Tibet, together with a numerical thermal model, constrains the RZT to have been active between 18 and 15 Ma at an average slip rate of 5 mm/year. This activity places the RZT out of sequence in an otherwise general pattern of propagation of south-directed thrusts toward the Himalayan foreland but appears to fill a gap in time that is not represented by current estimates of the timing of the other recognized thrust faults in the Himalaya and southern Tibet.

Objectives

The Indo–Asian collision is our best natural laboratory in which to understand the interplay between the various factors that control surface elevation, such as lithospheric thickening, injection of the ductile lower crust, temperature increases, or density decreases in the lithosphere and underlying mantle. Although central to understanding the geologic evolution of the collision zone, the history of crustal-scale thrusting in southern Tibet and the Himalaya is incompletely known. Geologic investigations conducted in southern Tibet by UCLA and LLNL personnel led to the recognition of two previously undocumented thrust systems: the north-dipping Gangdese Thrust (GT) and the younger south-dipping Renbu Zedong Thrust (RZT). The GT is known to have been active near Zedong in southeastern Tibet between 27 and 23 Ma. The younger RZT is in most places thrust over the trace of the GT obscuring its exposure, and the development of both systems has obscured the suture between India and Asia. Although we now have reasonably good control on the timing of motion on the GT, constraints on RZT motion are poor. To improve our understanding of this important structure, we undertook an investigation to determine the thermochronologic and thermobarometric evolution of the upper and lower plates of the RZT in order to constrain the timing and magnitude of slip on this feature.

Progress

K-feldspar $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronological results from granitoids of the Late Cretaceous–Early Tertiary Gangdese batholith in southern Tibet show evidence of a complex thermal history due to interactions among several structural elements.¹ The granitoids were buried during the Miocene beneath the north-directed RZT by Tethyan metasediments derived from the Indian shelf. Adjacent to the trace of the RZT, the hanging wall is characterized by amphibolite-grade metamorphism. Within the footwall, granitoids close to the RZT exhibit recrystallization to greenschist facies assemblages. K-feldspar samples from a northeast–southwest traverse extending 15 km away from the trace of the RZT near Lian Xian are consistent with argon loss due to heating that culminated at about 10 Ma. Using a variational method, we computed a representative spectrum of thermal histories consistent with the measured K-feldspar age and kinetic properties. Contour plots of probability density calculated from the best-fit solutions yield the full range of temperature–time constraints afforded by the samples. Samples far

removed from the RZT are well described by regional slow cooling from 300 to 275°C until about 10 Ma. Thermal histories for samples close to the thrust contact indicate that they have been differentially displaced along the RZT and are consistent with slip occurring at an average rate of 5 mm/year between 19 and 15 Ma and continuing at a lower rate until 11 Ma. The rapid cooling episode recorded by all the K-feldspar samples beginning at about 10 Ma is interpreted as the result of regional uplift of southern Tibet due to displacement along the ramp of the Main Himalayan Thrust.²

Some details of the pattern of thrust activity in the Himalaya and southern Tibet are emerging. The Gangdese Thrust, the earliest identified crust thickening event, is believed to have been active from >27 to 23 Ma (Ref. 3). The Main Central Thrust (MCT) is thought responsible for production of the High Himalayan leucogranites which range in age from 24 to 19 Ma (Ref. 4) and thus suggests a similar age range for MCT activity.⁵ Activity on the Main Boundary Thrust initiated at ~11 Ma (Ref. 6) and continued into the Pleistocene. Our inference that the Renbu Zedong Thrust was active between 18 and 11 Ma places this feature out of sequence in an otherwise general pattern of propagation of south-directed thrusts toward the foreland. However, it appears to fill a gap in time that is not represented by current estimates of the timing of the other recognized thrust faults.

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The Effect of Pressure on Oxygen and Silicon Diffusion in Olivine

Principal Investigators: Daniel L. Farber and Kevin D. McKeegan
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LLNL Collaborator: Frederick J. Ryerson

Abstract

Because olivine is the most abundant mineral in the upper mantle, a detailed understanding of its nonelastic transport properties is critical to our ability to describe flow in the upper mantle. Moreover, the pressure dependence (i.e., activation volume) for dislocation creep in olivine is poorly constrained. Thus, we have undertaken a series of experiments aimed at characterizing diffusion parameters for the rate-controlling species (silicon and oxygen) in olivine. Such data will yield an independent experimental constraint on the activation volume for flow in the upper mantle.

Objectives

Both the style and overall dynamics of flow within the mantle are, to a great degree, controlled by the nonelastic transport properties of high-pressure phases. In regions devoid of phase transformations, such as the upper 400 km of the mantle (where olivine is the dominant phase), modulation of such properties comes about through the pressure and temperature dependence of the process.¹ In olivine, the temperature dependence of properties such as dislocation creep and lattice diffusion has been well studied at 1 atm, yet the pressure dependence of such properties is still poorly constrained. While the rate of dislocation creep in olivine has been characterized to pressures of 2.5 GPa, controversy still remains as to the magnitude of the activation volume.^{2–4} Furthermore, if the activation volume for diffusion creep is significantly smaller than that for dislocation creep, the deformation mechanism in the upper mantle may change from dislocation-controlled to diffusion-controlled deformation with increasing pressure.¹

Recently, Karato et al.⁵ determined the activation volume for dislocation climb (a diffusion-controlled process) in olivine to pressures of 10 GPa. They report a value of 6 cm³/mol, whereas previous measurements suggested values as high as 19 cm³/mol (Refs. 6, 7). Because our ability to describe flow at the high-pressure, high-temperature conditions present within the mantle critically hinges on our knowledge of the activation volume for flow, the discrepancy in these numbers must be resolved. Because the rate of both dislocation climb and diffusion creep are controlled by diffusion, an independent characterization of the activation volume of these processes can be made by determining the activation volume for the slowest diffusing species (i.e., the rate-controlling step). Thus, our experiments are aimed at characterizing diffusion of oxygen and silicon—the two slowest diffusing species—in olivine.

Progress

Measuring diffusion rates of silicon and oxygen in olivine is hampered by the extremely short (about 1- μ m) diffusion profiles that can be produced on the time scale of a high-pressure experiment. However, because we are able to analyze our samples with the UCLA Cameca 1270 ion microprobe using a primary cesium beam, this is not as much an analytical problem of

measuring the profiles as it is an experimental problem in maintaining a highly polished surface at high-pressure and temperature conditions. Thus, in FY 1995, much of our effort has gone into determining experimental techniques to stabilize either highly polished or natural faces in olivine. Previously, we developed a technique for producing single-crystal forsterite with stable crystal faces. The single crystals are grown in strong platinum-lined nickel capsules containing about 100 μL of fluid. To date, we have grown usable forsterite from H_2^{18}O fluids yielding about 200- μm -diameter olivines of approximately $\text{Mg}_2\text{Si}^{18}\text{O}_4$ composition. Initially, we thought that these olivines could then be annealed in air at 1 atm to produce an $\sim$ thin film source followed by an anneal at high pressures to produce invertable diffusion profiles. Although we were able to produce $\sim$ thin film sources on the olivines, we found that the crystal faces become unstable during the diffusion anneals. Thus, we undertook a further series of experiments, annealing polished olivines in mixed C–O–H fluids at controlled $f\text{O}_2$ to find fluid compositions in which our sample surfaces remained stable.

These experiments have been completed, and we can now recover olivines that retain their high polish and thus allow for the analysis of short diffusion profiles. Moreover, we have started to extend this technique to the production of thin films of $\text{Mg}^{30}\text{Si}^{18}\text{O}_3$ atop the polished olivine surfaces. This material, when annealed with the isotopically normal MgSiO_4 single crystal, should allow us to obtain diffusion profiles for silicon as well as oxygen.

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Enhanced Sinterability of Shock-Compacted Zirconia-Toughened-Alumina Composites

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LLNL Collaborator: William J. Nellis

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Abstract

A two-stage gas gun has been used to study the densification and sintering behavior of dynamically shock-compacted alumina-zirconia powder. We have determined that the particle size distribution of the powder that was shock compacted had a significant effect on the densities, which were obtained in the as-compacted specimens and in the compacted and sintered specimens. In general, coarse particle size distributions attained higher as-compacted densities, while finer particle size distributions attained higher sintered densities. These results were compared to specimens that were fabricated using conventional process routes. The shock-compacted specimens exhibited densities about 20% higher than their conventionally processed counterparts.

Objectives

The increases in toughness and strength, which are facilitated by the incorporation of zirconia crystallites into ceramic composites, are well known. In order for the mechanisms that facilitate toughening of the material to operate, however, it is necessary to use processing conditions that will retain the submicrometer crystallite sizes, which will permit retention of the thermodynamically metastable t-ZrO₂ (tetragonal) polymorph. Dynamic shock compaction is a promising technique that has been used to consolidate a variety of powders through the rapid application of pressure. The high densities that are produced by this fast process are not accompanied by significant grain growth and have the potential to allow for the sintering of the composites to high final densities, containing microstructures that possess the fine grain sizes that are a prerequisite for enhancements in toughening. The objective of this research is to investigate the dynamic shock-compaction process of oxide powders and thus determine the process conditions that will produce dense, fine-grained microstructures in the sintered product.

Progress

Alumina and zirconia powders were mixed at the eutectic composition (67 vol% Al₂O₃) and rapidly solidified using an induction furnace and a twin roller device. This procedure produces nanocrystalline t-ZrO₂ grains embedded in an Al₂O₃ matrix. The powder was then milled and classified through microsieving and sedimentation techniques. The classification process produced powder distributions with average particle sizes ranging from 0.1 to 30 μm. Samples of about 0.2 g were loaded into stainless-steel shock fixtures that were impacted by a Lexan projectile traveling at approximately 1 km/s. The impact produced peak shock pressures in the powder ranging from 7.4 to 10.5 GPa. Each specimen was recovered crack-free except the 0.1-μm powder sample, which was extensively macrocracked. Except for the macrocracked compact, the samples were then sintered at 1650°C. For comparison, control samples were uniaxially cold pressed and sintered at the same temperature.

Figure 1 compares the densities of shock-compacted and control specimens before and after sintering. In this figure, the dashed lines represent the densities of the shock-compacted specimens, and the solid lines represent the densities of the cold-pressed specimens. In general, coarser particle size distributions produced higher presintered densities, while finer particle size distributions produced higher sintered densities. The data showed that the shock-compaction process produced about a 20% density increase in the green specimens and a 10 to 20% increase in the densities of the sintered specimens. The extent of the density enhancement diminished as the particle size was reduced.

Figure 1. Densities of the specimens before and after sintering. The shock-compaction process produced an increase in the density of the specimens before and after sintering.

Development of a Nuclear Method Based on Cosmogenic Nuclides ^{14}C and ^{10}Be for Determining Soil Erosion Rates

Principal Investigator: Devendra Lal (UC San Diego)

LLNL Collaborators: Robert C. Finkel, Marc Caffee, and John R. Southon

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Abstract

We are now in the final stages of developing and testing a novel nuclear method for determining soil erosion rates. It is based on the recent finding that several nuclides, stable and radioactive, produced by cosmic rays in terrestrial materials can be detected unambiguously in the soil matrix. If their production rates can be ascertained for different conditions of irradiation by cosmic rays, their concentrations can be related to geomorphic changes such as erosion and mass wastage of the soil–rock horizon. The nuclear method has previously been applied for studying geomorphic processes, but not for studying soil erosion.

We have made the first attempt in this direction by studying the evolutionary history of a soil profile with a quartz vein, based on the measured concentrations of in situ ^{14}C and ^{10}Be produced in the quartz vein. Further attempts are now under way to measure the concentrations of the two nuclides in residual quartz grains exceeding 1 mm in several soil profiles collected from the eastern Sierra Nevada, California. The soils are of glacial origin from moraines between the penultimate glaciation (stage 6, ca. 150,000 years ago) and the late Wisconsin maximum (oxygen isotope stage 2, ca. 20,000 to 14,000 years ago).

Objectives

Soils offer precious records of the climatic and erosional record for the Quaternary.^{1,2} Assessment of soil dynamics constitutes a central problem in soil management, which in turn determines the sustainable carrying capacity of the Earth for humans.³ Key questions are: What is the rate at which soils are formed by weathering as a function of climatic parameters? What is the dependence of soil erosion rates on various natural or anthropocentric processes?

It would appear that such questions would easily be answered using the suite of available radionuclide tracer techniques developed for other studies. However, soils are unique in several respects because they are “open” systems, both in the chemical and nuclear contexts. The hope for a viable solution of the key questions would be to identify unique mineral assemblages, which on the one hand are proxies for the progressive evolution of soils and on the other can be characterized as having well-defined physical and chemical histories. These assemblages should act as a “closed” system in the strictest sense to qualify them for a particular nuclear method. Applications of nuclear methods are now becoming a reality, and we have already attempted development of an innovative method to determine soil erosional history, based on in situ production of radionuclides by cosmic rays in an intact quartz vein in a soil profile, originally devoid of these nuclides. The cosmogenic in situ production of nuclides in terrestrial minerals (e.g., rocks, ice) has been exploited recently to determine their surficial histories.^{4–6} Our

studies are a natural extension of the idea of using cosmogenic in situ nuclides for studying rock erosion rates in these recent studies. We have already applied the method for the special case of the quartz vein in a soil profile. The results appear promising, giving hope that an extension to quartz aggregates normally present in soils would enhance its value for studying soils formed by weathering of acidic rocks.

Progress

Our efforts have taken two directions. First, we wanted to reduce the background, or what is known as the chemical blank, in the processing of rock quartz for ^{14}C (Ref. 7). The ^{10}Be technique has already been developed to a successful stage.⁶ Second, we decided to test the basis of the method by studying a soil profile, which offered greater convenience in measuring the *in situ* cosmogenic nuclides ^{14}C and ^{10}Be .

The soil profile chosen for the tests is situated on the south side of Lawyers Road, about one mile northwest of the center of Vienna, Virginia ($38^{\circ}54'\text{N}$, $77^{\circ}25'\text{W}$). The vein is exposed at the surface of a roadcut. The vein has no soil or vegetative cover; it is about 50 to 60 cm wide where exposed. Its surface parallels the local geomorphic surface. The quartz units are irregular masses to lenticular bodies. The largest are about 200 m wide and greater than 1000 m long at the surface. Samples consisted of several quartz chips chiseled off from the vein. Their depths were measured vertically from the surface of the soil, which is relevant for cosmic-ray interactions. For ^{14}C and ^{10}Be analyses, the quartz samples were first crushed to less than 150 μm and cleaned chemically with HF/HNO_3 . The extraction of ^{14}C was performed by digesting the sample in 25% HF in vacuo in the presence of about 1.5 cm^3 each of CO and CO_2 carrier gases, which were devoid of ^{14}C activity.⁷ The digestion was done in a Kel-F container. Kel-F, a homopolymer (chlorotrifluoroethylene), is resistant to HF and also does not measurably absorb any CO or CO_2 on its surfaces. Two carrier gases are used because an appreciable fraction of cosmogenic in situ ^{14}C is in the form of CO , allowing us to minimize interference from environmental ^{14}C , which is in the form of CO_2 .

For a steady-state erosion model, the measured concentration, N , is related to the rate production of a spallogenic radionuclide at the eroding surface:⁵

$$N = \frac{P}{\lambda + \mu(\epsilon)} \quad (1)$$

where λ is the disintegration constant of the nuclide, ϵ is the erosion rate, and μ is the absorption coefficient for cosmic-ray particles in the matrix. The absorption mean free path for cosmic rays is taken to be 150 $\text{g} \cdot \text{cm}^{-2}$ (Ref. 5). Adopting a mean value of 2.7 g/cm^3 for the density of the quartz vein and the soil matrix, the value of μ is $2.7/150 = 1.8 \cdot 10^{-2} \text{ cm}^{-1}$.

Using such models, we can then deduce the erosion rate and the effective time period for which the rock has been eroded for the two nuclides. A consistent result for the two nuclides would imply a simple erosional history. However, we found that the results for the two nuclides differed substantially (see Table 1).

Table 1. Inferred model erosion rates and effective exposure ages of the quartz vein.

Nuclides	Mean erosion rate (cm · year ⁻¹)	Effective exposure age (years)
¹⁴ C	$\geq 3 \times 10^{-3}$	$> 5.7 \times 10^3$
¹⁰ Be	$< 3 \times 10^{-4}$	$> 1.8 \times 10^5$

Steady-state erosion models with dynamic changes—for example, sporadic removal of a slab from the surface or burial of the surface with sediments—have been dealt with recently.⁵ A convenient way of delineating geomorphic processes is to consider ratios of two nuclides. The ratios for different pairs of nuclides among ¹⁴C, ²⁶Al, and ¹⁰Be were considered by Lal.⁵ From these discussions, it becomes clear that if the erosion rate at a site changes slowly or abruptly with time, one cannot obtain ¹⁴C/¹⁰Be relative concentrations as observed (see Figures 5 and 7 in Lal⁵). The observed ratios are uniquely consistent with a model where the quartz vein at first eroded at the slower of the two erosion rates given in Table 1 (i.e., $\leq 3 \times 10^{-4}$ cm · years⁻¹). After an irradiation over a period of $\geq 1.8 \times 10^5$ years since its exposure, it was then buried abruptly or slowly by a thickness of soil, ΔX , exceeding 1.3 m, to result in a preferential decay of accumulated ¹⁴C over ¹⁰Be in the vein. The burial period has to be greater than 2 mean lives of ¹⁴C (i.e., $\geq 2 \times 10^4$ years), to lower the ¹⁴C/¹⁰Be ratio acquired in the previous irradiation by an order of magnitude. Several scenarios are possible, depending on the value of ΔX . After this burial event, the soil surface could have continued to erode at the preburial rate. Higher and lower erosion rates are permitted by the available data on the nuclides ¹⁴C and ¹⁰Be. The number of steps or events in the erosional history, which can be delineated by such observations, is obviously dictated by the number of radionuclides of different half-lives for which in situ concentration data are available.

The erosional model proposed above seems to be in conformity with the known geologic history of the site. Shorter-term processes may cause periodic burial and exhumation of the quartz body surfaces. Although poorly documented at present, there is evidence of a 50- to 80-cm-thick aeolian loess along the inner edge of the Coastal Plain near the Piedmont sampling site.⁸ In the context of general denudation of the Piedmont at a surface lowering rate of 5 to 20 m/10⁶ years (Refs. 2, 9), there may have been shorter-term cycles of rapid deposition of about 50 cm of loess or colluvium and reexhumation of surfaces because of soil wash erosion processes. How many cycles may have occurred is impossible to determine at this time, but the proximity of this area to the terminus of continental glaciers (e.g, central Pennsylvania, northern New Jersey) suggests the possibility that climatic cycles of deposition and erosion have been active in the northern Virginia Piedmont on a 10⁴- to 10⁵-year time scale. The most recent deposition cycle at 10,000 years may have provided sufficient shielding to cause reduction of the ¹⁴C concentration relative to the ¹⁰Be concentrations.

We are now studying a suite of soil profiles of glacial origin from moraines in the eastern Sierra Nevada, California. These soils were chosen because their weathering duration and history are fairly well known. The soils were deposited between the penultimate glaciation (stage 6, ca. 150,000 years before present) and the late Wisconsin maximum (oxygen stage 2, ca. 20,000 to 14,000 years before present). We are hopeful that the ongoing measurements will provide a critical test of the nuclear method for studying the soil erosion rates.

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Shock Compaction of Ferromagnetic Particles

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Abstract

Fine ferromagnetic particles (1 to 10 μm) of SmCo_5 were shock compacted using the two-stage, light-gas gun at LLNL. Bulk magnetic disks were produced in an applied pressure range of 1.7 to 27.0 GPa. The microstructure of the shock-compacted disks was studied using scanning electron microscopy (SEM) and x-ray diffraction (XRD). A SQUID magnetometer was used to analyze the magnetic properties of the compacted disks. Between 2.0 and 9.0 GPa, the coercivity remains constant, while both the remnant and saturation magnetization exhibits peaks. Above 10.0 GPa, all the magnetic properties show a sudden decrease.

Objectives

Forming bulk magnets from fine particles is desirable because of the high coercivity of small particles. Bulk magnets are produced commercially by sintering fine particles. Sintering, unfortunately, induces grain growth. Our approach is to magnetically align fine particles (micrometer sized) with few domains per particle and to consolidate them into a bulk form by applying dynamic pressures. Shock compaction permits use of very high pressures (about 10 GPa, well above the strength of the fine particles) for a short time ($<1 \mu\text{s}$), which results in high densities without grain growth.

The bulk magnetic properties of the rare-Earth permanent magnets, such as SmCo_5 and $\text{Nd}_2\text{Fe}_{14}\text{B}$, are heavily influenced by its microstructure. Shock compaction induces defects in the microstructure that can affect the bulk magnetic properties. By varying parameters such as shock pressure and grain size, we can modify the microstructure and, hence, the bulk magnetic properties.

The goal of our study is to consolidate fine particles of SmCo_5 into dense compacts. The effects of shock pressure on the microstructure and the standard magnetic properties of remnant field, intrinsic coercivity, and saturation magnetization will be analyzed.

Progress

Fine particles of SmCo_5 were produced from both commercial powder and arc cast ingots by mechanical ball milling. The resultant particles have a size distribution from 1 to 10 μm , as determined from scanning electron microscopy. The powder was prepared in two different ways prior to shock compacting. In one case, the powder was aligned in a 1-T field and pressed into a compact. The remaining samples were prepared by tapping the powder directly into the shock capsules. The 7-m light-gas gun at LLNL was used to compact the powder in a pressure range of 1.7 to 27.0 GPa. The shock compaction produced thin, hard disks of SmCo_5 about 1 cm in diameter.

Shock compaction at pressures less than 2.0 GPa failed to completely consolidate the particles. The shocked disks have little mechanical strength and tend to crumble easily. Between 2.0 and 10.0 GPa, the shock processing produced a single well-consolidated disk. The estimated average density for the whole shocked disk was 80 to 88% of the theoretical value, although the

density varies on a local scale. Above 6.0 GPa, the stress of the re-shock begins to tear apart the sample. At higher pressures, the shock energy causes melting of the sample at the edges. At 18.0 and 27.0 GPa, the shock release tears the sample completely apart, and the shock energy causes the SmCo_5 to undergo thermodynamic phase changes.

The composition of the shock-compacted disks was checked with x-ray diffraction. The x-ray patterns showed no changes in the composition for all shock pressures less than 18.0 GPa. At 18.0 GPa and above, the SmCo_5 decomposes into $\text{Sm}_2\text{Co}_{17}$.

Magnetic measurements were made at UC San Diego with a superconducting quantum interference device magnetometer. Small disks (diameter of about 2 mm) were cut from the larger disks. These disks were measured for their magnetic properties with the applied field perpendicular to the plane of the disk. The remnant field B_r (the residual magnetization when the applied field H is zero), intrinsic coercivity H_{ci} (the applied field needed to reduce B_r to zero), and the saturation magnetization (the maximum value of the magnetization) were extracted from hysteresis loop measurements.

In the pressure range of 2 to 9 GPa, the shocked samples exhibit a high intrinsic coercivity, which is comparable and slightly higher than the reference sample at 0 GPa. Below 2 GPa, the samples have lower coercivity because of the incomplete bonding. Above 10.0 GPa, the intrinsic coercivity drops dramatically, then levels off. The saturation magnetization increases monotonically with increasing pressure until 10.0 GPa, then drops off suddenly. The decrease is consistent with the drop in coercivity. The remnant magnetization, B_r , rises monotonically and reaches a maximum between 6.0 and 10.0 GPa. Above 10.0 GPa, B_r falls off although the values above 18.0 GPa increase because the $\text{Sm}_2\text{Co}_{17}$ phase is present. A fit of the hysteresis loop data at high magnetic fields to the law of approach suggests an increase in microscopic inclusions and correlates with the decrease in H_{ci} and M_s (Ref. 1).

The pressure dependence of the magnetic properties differs from that of shock-compacted bulk samples of SmCo_5 . For bulk SmCo_5 , the key magnetic properties exhibit a dramatic falloff for even moderate pressures. For our samples, most of the shock energy is absorbed in bonding the individual grains together rather than inducing shock defects. This absorption accounts for the nominally high values of the magnetic properties in the range of 2.0 to 10.0 GPa for our samples.

We have shown that shock consolidation is a useful technique for producing bulk permanent magnets from fine particles. The technique does not alter the composition and retains the inherent properties of the particles. The next step is the fabrication of shock-consolidated magnetic composites. We have begun work on creating a composite of $\text{Nd}_2\text{Fe}_{14}\text{B}$ and Fe. We hope to combine the high coercivity of $\text{Nd}_2\text{Fe}_{14}\text{B}$ and the high moment of Fe. This could potentially produce an improved permanent magnet material.

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Element Partitioning between Silicate Melts and Crystals: Constraints on Magmatic Segregation and Transport Processes from the Uranium Decay Series

Principal Investigator: Quentin Williams (UC Santa Cruz)

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Abstract

We have characterized the partitioning behavior of Li, B, and Be between clinopyroxene and a range of coexisting silicate melts. These results, which represent the first characterization of the chemical behavior of these elements in magmatic systems, are relevant to the manner and rate at which cosmogenic nuclides in subducted sediments are extracted via arc magmatic processes. Moreover, they provide constraints on the degree to which these elements have been extracted from the bulk Earth and, thus, produce a bound on the extent to which these elements have been segregated into Earth's crust. Our data demonstrate that Be is the least compatible of these elements, being retained in crystalline material at only 0.2 to 1% of its abundance within coexisting silicate liquids, whereas Li (the most compatible of these three) is retained in crystalline clinopyroxene at 12 to 24% of its abundance within coexisting liquids.

Objectives

The motivation for determining the composition of coexisting crystals and magmatic silicate liquids is straightforward: Melting is the primary mechanism through which the planet has differentiated, and a detailed understanding of the melting process provides first-order constraints on the chemical evolution of the Earth. The specific goals of our project are to determine the liquid–solid partitioning behavior of two families of elements: (1) the relatively large ionic radii actinide elements of the U-decay series; and (2) at another geochemical extreme, the small ionic radius light elements, Li, Be, and B.

We previously characterized the behavior of some of the former set of elements,¹ and work focusing on Pa and Ra partitioning is ongoing; the latter set of elements represents a new direction of our studies, and is designed to provide a detailed understanding of the efficiency of the geochemical cycling of these elements in subduction environments. The appearance of cosmogenic ¹⁰Be, with a half-life of about 1.5 million years, within arc magmatic environments (such as in Aleutian stratovolcanoes) implies that surficial sediments are rapidly subducted, and that a comparatively short-lived geochemical signature is present in the source region of circum-Pacific volcanism. Our goal is to draw quantitative constraints on the transport of Be in this arc environment and to evaluate the efficiency of extraction of Be, B, and Li from the mantle of the planet.

Progress

We have measured the partitioning behavior of Li, B, and Be between the common upper-mantle phase clinopyroxene and silicate melt over a number of compositions in the CaMgSi₂O₆–CaAl₂Si₂O₈–NaAlSi₃O₈ ternary. Magmas in this system span compositions relevant to a wide range of

volcanism, from that at mid-ocean ridges (with SiO_2 contents of about 50 wt%) to subduction-related volcanism (with SiO_2 contents of about 62 wt%). A crucial component of our studies is to evaluate the role of magma chemistry in changing the ability of magmas to strip elements from coexisting solids: in effect, to determine how much the magma changes the chemistry of the solids through which it passes and how much the magma itself is changed during the transport process. We previously demonstrated that Al content of magmas plays a vital role in the degree to which actinide elements enter into silicate liquids.¹ Curiously, this unexpected observation also appears to be robust for beryllium, as well, at the other end of the ionic size spectrum of elements (Figure 1).

Figure 1 demonstrates that the efficiency of beryllium extraction via the melting process is exceedingly high. For melts with low aluminum contents, slightly less than 0.3% Be resides in the coexisting crystalline material. Even for high-Al melts, this value remains near 1%. The importance of these low partition coefficients is threefold. First, if melt geochemically interacts with its surroundings on ascent via a chromatographic process (as appears likely), the rapidity with which Be will be moved will be essentially equivalent to the velocity of magma motion; no retardation will be produced by retention of an element within the slower moving solid phases through which the melt percolates. Thus, observations of the presence of ^{10}Be in arc magmas need not necessarily be associated with large-scale sediment subduction. Because of the rapid transport of Be once it reaches the zone of

Figure 1. Effect of aluminum content in the liquid on the clinopyroxene–melt partition coefficient for beryllium in the albite–anorthite–diopside system at 1200°C.

partial melting during subduction, relatively minor amounts of sediment could generate the observed geochemical observations. Second, it appears likely that beryllium is one of the elements most effectively extracted from solid material via melting processes. By comparing the abundance ratios of B, Be, and Li, we can characterize the degree of source enrichment or depletion. Indeed, we would predict that any previous exposure to a melting process (whether at mid-ocean ridges or in subduction environments) would dramatically alter the Be/B and Be/Li ratios present in magmas. Finally, if much of the mantle has been exposed to melting processes (as has been inferred), the crustal abundance of Be may largely reflect the planetary abundance of this element.

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Empirical Determination of a Soil Production Law Using Topographic Data, Measurements of Soil Depth, and Cosmogenic Nuclides

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Abstract

We measured concentrations of in situ-produced cosmogenic ^{26}Al and ^{10}Be nuclides in bedrock samples taken at different soil depths on divergent ridges. We sampled three regions with similar hillslope morphology, but markedly different climate and geologic histories: (1) the Oregon Coast Range near Coos Bay; (2) the coastal hills near San Francisco (Tennessee Valley); and (3) the hills south of Canberra, Australia. Our measurements were made to determine the long-term erosion rate of each sample. Under steady-state conditions, this rate defines the rate at which soil is produced from the underlying bedrock as a function of soil depth. We also measured the divergence of slope and soil depth at our Marin County, California, site to test the theoretical result that soil thickness varies with hillslope curvature. Our measurements from this site offer the first clear support for the hypothesized exponential soil production law. Although the number of samples studied is far too small to address our long-term goals of determining a soil production law, our results show the viability of our methods and yield valuable soil production rates for our study areas.

Objectives

Our goal was to develop two independent field-based methods to test for the first time the validity of the hypothesized depth dependency in the soil production rate. For more than 100 years, scientists have assumed that the rate of disintegration of bedrock into erodible soil depends on the thickness of the overlying soil mantle. This assumption underlies the belief that there are weathering-limited and transport-limited landscapes and is not supported by any field data. It also identifies a key linkage between climate, topography, geology, and erosion. Recent analysis suggests that on divergent hillslopes (ridges) where soil production is in balance with soil removal by diffusive processes, the product of the diffusion coefficient and hillslope curvature equals the soil production rate.¹ We hypothesize that, if soil production rate depends on soil thickness, then soil thickness should vary with topographic curvature. If this hypothesis is correct, we can then fully quantify the soil production law if the diffusion coefficient is known for the study site.

We also sought to independently determine the soil production law by measuring in situ-produced cosmogenic ^{10}Be and ^{26}Al in quartz extracted from bedrock under different soil depths. This approach is analogous to erosion rate estimates previously done on exposed bedrock using cosmogenic nuclides, but we sampled target rock beneath the surface, at the distinct soil-bedrock interface, as well as bedrock exposed at the surface of the landscape.

Progress

Geomorphology. We surveyed three divergent ridges in Tennessee Valley, California, at 1- to 3-m resolution and measured soil depth at 172 locations. We calculated hillslope curvature for each location. Figure 1 shows the observed relationship between soil production rate (estimated from the product of diffusivity and local curvature) and local soil depth.² We find a clear inverse relationship between inferred soil production rate and soil depth, although the scatter is considerable. This scatter is to be expected even for steady-state soil thickness because of (1) fine-scale heterogeneity (fracture density, bedding, etc.) in the resistance of the underlying bedrock to soil production; (2) fine-scale curvature variation due to the same mechanism; and (3) short-term variation in biologic activity (which will affect local soil depth more than curvature) such as gopher burrowing. We used various topographic grid sizes to determine hillslope curvature and found that 5-m grids generated the least variance. Despite the variance, these data seem to support a simple exponential production function rather than one with a maximum at some nonzero depth.

We also surveyed and measured soil depth from the divergent areas from our Coos Bay, Oregon, study site and are working to develop the relationship between soil depth and hillslope curvature. Both sites are underlain by greywacke and were used to fully develop our methodology.

Geochemistry. We collected bedrock samples from three of our project areas and successfully measured ^{10}Be and ^{26}Al concentrations to calculate long term erosion rates assuming steady-state conditions. We analyzed six

Figure 1. A soil production function estimated from field data from Tennessee Valley, California, plotted with preliminary results from our nuclide analyses. Solid curve shows the exponential fit to 172 depth and curvature measurements on divergent slopes, assuming constant diffusivity and densities. Dashed curves illustrate hypothetical production functions for our San Dimas and Australia sites.

samples from our Marin County, California, site (from soil depths of 0, 16, 30, and 55 cm) to develop an initial estimate of the soil production function. We calculate long-term erosion rates of 32.2 ± 4.5 , 37 ± 11 , 18.2 ± 2.7 , and 14.1 ± 0.8 m/million years from these samples taken at the base of the soil column. These data are also plotted in Figure 1 to show the correlation with the geomorphologically derived soil production function. Our initial results from the Oregon and Australia sites compare favorably with long-term average estimates at each site. In Oregon, the background value is about 70 m/million years (Ref. 3), and the average of our two samples yields 63 m/million years. The long-term erosion rate for our site in Australia is about 1 m/million years (Ref. 4), while our calculated rate is 8 m/million years. In addition, we use Figure 1 to show hypothetical soil production functions for our southern California (not sampled yet) and Australia sites to illustrate the potential variation of the soil production function under the wide range of climates and erosion rates.

The California samples, however, remain puzzling to us. They tend to lie outside the region allowed for simple exposure and erosion in the plot of $^{26}\text{Al}/^{10}\text{Be}$ versus ^{10}Be . On the face of it, they would seem to have had a long (several hundred thousand years) history of complex burial and exposure. The four initial samples were selected over a range of lithologies to test our methods, and they were collected from different locations. Therefore, it does not seem likely that analytical problems are at the root of the puzzle. We hope to resolve this confusion with data from samples currently being analyzed.

We intend to use our cosmogenic nuclide-based method, which depends on the high analytical sensitivity of the LLNL Center for Accelerator Mass Spectrometry, to provide both an evaluation of the procedure and some insights about the assumption of steady-state soil production. We also intend to combine measurement of soil production rate through cosmogenic nuclide analysis on ridge crests, where bedrock typically is exposed, with our measurements of hillslope curvature to independently determine local diffusivity. Additionally, our analysis of ^{10}Be and ^{26}Al concentrations with their different half-lives will allow us to directly assess the assumption of steady-state soil thickness, because the ratio of the nuclide concentrations will differ from that in the steady-state case if the soil mantle thickness is not steady through time.

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Variation of Regional Seismic Discriminants with Surface Topographic Roughness in the Western United States

Principal Investigators: Susan Y. Schwartz and Thorne Lay (UC Santa Cruz)

LLNL Collaborators: William R. Walter, Kevin Mayeda, and Howard Patton

Other Collaborator: Tian-Run Zhang (UC Santa Cruz)

Abstract

Regional distance P and S waves behave differently with propagation distance because of complex elastic and anelastic effects in the crustal waveguide and uppermost mantle. It is well recognized that seismological discriminants based on P/S ratios or individual-phase spectral ratios must be corrected for regionally dependent path effects for successful discrimination to be achieved. Such corrections usually involve only distance-dependent decay, parameterized to account for geometric spreading and attenuation factors averaged over some geographic region. However, large scatter persists in distance-corrected discriminants, which degrades their performance. Strategies are needed to further reduce the scatter by accounting for individual path variability.

We demonstrate that characterizing some of the path variability by the readily measured surface topographic roughness along each path allows reduction of the scatter in some regional discriminants. Pg/Lg and Pn/Lg ratios and PR'Pn and Lg low-frequency/high-frequency spectral ratios for 80 earthquakes in the western United States recorded at four stations of the Livermore Nevada Test Site (NTS) Network are analyzed for path effects. Although all of these discriminants display distance dependence, log Pg/Lg is also found to be significantly correlated with surface roughness. The correlation is emphasized when the product of distance and roughness is used as an independent variable, and the data in the frequency range of 1 to 4 Hz have the strongest trends. Corrections based on the correlations with distance and roughness can reduce the variance of the log Pg/Lg discriminant by 22% in the 2- to 4-Hz band. It appears that coupling of the Pg and Lg energy, which reverberates in the crust, accounts for the sensitivity to the gross waveguide properties manifested in the surface roughness parameterization. The results support the concept of pursuing path corrections beyond purely range-dependent trends.

Objectives

Amplitude ratios and spectral shapes of various types of P and S waves recorded at regional distances have been explored for decades as potential discriminants for identifying seismic sources. Lateral variations in the elastic and anelastic structure of the crust and uppermost mantle produce regional differences in the amplitude and spectral behavior of regional phases. The associated path effects must be accounted for, both to reduce the scatter in the discriminants and to transport discriminant behavior from one region to another. Reducing the scatter in promising regional seismic discriminants has thus become a major element in strategies for monitoring a comprehensive test ban treaty and is the focus of this work.

In this project, we analyzed seismograms from 80 earthquakes in the western United States recorded at four stations of the broadband Livermore NTS Network, so we could determine path effects on regional discriminants. The western United States is tectonically active, and path properties are expected to be quite heterogeneous. Therefore, we considered both the distance behavior and path roughness behavior of Pg/Lg ratios at different frequencies. We lacked reliable theoretical models for the range dependence of the separate phases, and attenuation and geometric spreading effects are difficult to separate; therefore, we were searching for a simple general distance dependence.

Correction for the net propagation effects requires only a reliable knowledge of the frequency-dependent distance dependence of the ratio, not the separate behavior of the different phases. For parameterizing the distance decay, we used an exponential form, assuming:

$$R(\Delta) = 10^{\gamma\Delta}, \quad (1)$$

where R is the Pg/Lg ratio, Δ is the distance in kilometers, and γ is the slope of the empirical regression line between $\log R$ and A . Figure 1a shows the distance dependence of Pg/Lg for the frequency band of 2 to 4 Hz for our western U.S. paths. In this passband, the distance dependence r is slightly positive, and it remains positive up through the 8- to 10-Hz passband.

We now consider the path effects characterized by roughness, as measured by the root-mean-square (RMS) value, of the surface topography along each path. Log R correlates with RMS surface roughness about as strongly as with distance. Figure 1b shows the behavior of the 2- to 4-Hz band. Note that the correlations with distance (Figure 1a) and surface roughness (Figure 1b) display similar overall trends. The two independent variables, distance and roughness, have a correlation coefficient of only 0.08, so these are not redundant effects.

One can define corrections based on these separate parameters, but we explored whether a combination of parameters is superior. We considered an end-member case in which the distance behavior of Pg or Lg is controlled by path roughness. As a simple assumption, we let r be a linear function of roughness, that is:

$$\gamma(\mu) = \alpha\mu, \quad (2)$$

where μ indicates RMS topographic roughness, and α is a constant coefficient. Then Equation (1) becomes:

$$R(\Delta) = 10^{\alpha(\Delta\mu)}. \quad (3)$$

Figure 1c shows the correlation of $\log R$ with the product of distance and roughness, $\Delta\mu$. The correlation coefficient is higher than that for each variable separately. The variable $\Delta\mu$ can reduce more scatter in the data than the separate terms in this frequency band. It appears that r is dependent not only on region but also on propagation direction in a given region.

The objective of all path corrections is to reduce the variance in the discriminant population so that subtle source effects can be detected. The variances of uncorrected $\log R$ and ratios corrected for $\Delta\mu$ were calculated in each passband. The variances are reduced after correction for $\Delta\mu$ to variable extent for different frequencies, which is also true of corrections for just distance or just roughness. In the frequency range of 2 to 6 Hz, $\log R$ shows the

Figure 1. Log Pg/Lg as a function of (a) distance, (b) roughness, and (c) distance $\times$ roughness for the western U.S. data in the frequency band of 2 to 4 Hz.

greatest distance and roughness dependence and the largest variance reductions (up to 22%) upon path correction.

We have considered only a very simple form of path property, and there is good reason to expect that other path characterizations such as sedimentary basin thickness, crustal thickness, or gradients in these parameters (e.g., Zhang et al.¹) may provide comparable or additional variance reduction in the discriminants. However, surface topography is by far the highest resolution, most precise information that will ever be available for any given region. Thus, it is encouraging that reasonably strong variance reductions can be achieved in some cases using this simple characterization of the path.

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Three-Dimensional Modeling of Upper Mantle Structure beneath the Western United States

Principal Investigator: Yu-Shen Zhang (UC Santa Cruz)

LLNL Collaborator: Howard J. Patton

Abstract

We are developing a high-resolution shear velocity model of the western United States. Because the resolution scales differ in recent regional and global studies, velocity structures in the uppermost mantle (less than 300 km) under the western United States are different. For example, there is a deep, slow-velocity anomaly at depths between 100 and 300 km with horizontal radius of about 500 km in the southern Basin and Range, which has not been discussed before, but which may have important implications for the dynamics of the Basin and Range. These studies must be improved to allow geodynamic understanding of this tectonically active area.

Objectives

Using Love- and Rayleigh-wave dispersion measurements, we propose to develop a three-dimensional, shear-velocity model for the upper 300 km of the mantle under the western United States. In this project, we are using the surface wave at periods between 50 and 150 s, which is sensitive to the upper 300 km of the mantle, and the earthquakes that occurred from 1980 to 1994 with magnitude ≥ 5 . The effects of model parameterization and inversion methods will be discussed to ensure the accuracy of the results. The final high-resolution shear-wave velocity model, with a resolution of about 200 to 400 km, will provide a framework for multidisciplinary studies of the western United States.

Progress

In FY 1995, we completed the data-collection phase of this study. Because the accumulated digital seismic data in the last decade have provided excellent path coverage, we originally planned to collect only digital seismic waveforms recorded by the IRIS network. However, we found that the LLNL network has an excellent dataset, which has not been fully exploited and will improve the coverage greatly. Therefore, we extended the data collection to include the LLNL network recordings from 1990 to 1994. Figure 1 shows part of the path coverage for Rayleigh waves at period of 100 s. We want to use all possible data and to improve the resolution.

The data processes are conducted in the spatial and spectral domains simultaneously to ensure the inversion is as accurate as possible. Different model parameterization methods, including continuous model parameterization, discontinuous model parameterization, and changing of model parameterization sizes, will affect the inversion results in the global investigation. We are conducting a series of tests to check these effects and to find the best model parameterization.

Figure 1. Map of the western United States showing part of the path coverage for Rayleigh waves at a period of 100 s.

Crustal and Uppermost Mantle Structure from Observations of SPdP

Principal Investigator: Peter Shearer (UC San Diego)

LLNL Collaborator: William R. Walter

Student: Paul Earle (UC San Diego)

Abstract

Observations of SPdP phases recorded on broadband seismic stations in North America have previously been used to infer the existence of an increase in seismic velocity at a depth of 70 km.¹ These phases arrive shortly after the shear (S) waves and are sometimes of comparable amplitude, but with a distinctly different particle motion. Our study extends this previous work to a global survey and expands the synthetic seismogram modeling tests. SPdP is a seismic phase that travels through the mantle as an S wave and is converted at the surface to a compressional (P) wave, which undergoes a topside reflection from a seismic discontinuity at a given depth. Reflectivity synthetic modeling has shown that care must be taken to isolate SPdP arrivals originating from top-side Moho reflections (SPmP) before discontinuities in the uppermost mantle can be interpreted. Thus, we have developed and applied a method, using SPmP arrivals, to determine crustal thickness.

Stacking techniques applied to broadband records reveal similarities between these sometimes complicated arrivals. Such stacks show energy arriving at a time and distance range consistent with reflections from a discontinuity in the uppermost mantle. S-to-P converted phases can also be used to look deeper in the mantle; reflectivity synthetics for the PREM and IASP91 models differ significantly over the distance range of 75 to 85 deg. These differences arise from the existence of a 220-km discontinuity in PREM, which is absent in IASP91. We are examining available data to determine if these phases can be used to verify the existence or absence of the 220-km discontinuity.

Objectives

Our goal in this project is to determine the global extent and properties (depth and impedance contrast) of discontinuities in the uppermost mantle from observations of S-to-P converted phases and to place upper bounds on their magnitude in regions that produce no observable reflections. An improved knowledge of the seismological properties of these discontinuities would provide constraints on upper-mantle composition and dynamics.

Progress

Discontinuities below the Moho cause triplications in the SP travel-time curve and enhanced amplitudes in the waveforms. Synthetic seismogram modeling shows that these amplitude “bright spots” are confined to certain source–receiver ranges for a given discontinuity depth. To determine if such energy can be clearly detected, we computed synthetic seismograms using the reflectivity method, to obtain the response expected for a suite of models with different crustal thicknesses and upper-mantle velocities (P_n) and with the possible inclusion of an 80-km discontinuity. The Moho-reflected SP phase is a prominent feature, and knowing its behavior is crucial for avoiding possible misidentification of upper-mantle discontinuity phases. Synthetics for varying crustal thicknesses show that increasing the crustal depth

widens the separation between S and SPmP but does not significantly increase the distance to which SPmP is observed (see Figure 1). Enhancing the Pn velocity of the models has the opposite effect, increasing the distance range of SPmP observations while only slightly changing the separation of the S and SPmP phases. Difficulties arise when a thick crust is accompanied by an unusually large Pn velocity. Under such conditions, synthetic seismograms predict energy arriving at distances and times consistent with a reflection from a shallow upper-mantle discontinuity (60 to 80 km). Thus, knowledge of the crustal depth is essential to accurately identify discontinuity phases. We developed a new method for estimating crustal thickness using the SPmP phase. The crustal thickness is determined from the differential travel times of S and SPmP (Figure 2). So far, we have estimated crustal thickness for 17 stations (Figure 3). The only free parameter in our modeling is the average P velocity in the crust; therefore, we should be able to combine these measurements with receiver functions, being sensitive to the P-to-S velocity ratio, and estimate Poisson's ratio in the crust.

We searched more than five years of IRIS broadband data for possible SPdP phases. Considerable effort was involved in archiving records and software development to provide efficient access to the more than 100,000 teleseismic recordings. Our examination of approximately 14,000 three-component seismograms at the optimal source–receiver separation highlighted the waveform complexities that arise from various effects, such as differing source time functions, crustal reverberations, and varying attenuation. In hopes of determining the global nature of possible discontinuities in the uppermost mantle, we use robust stacking techniques to reveal the underlying shared signal in the broadband waveforms. The particle motions of the S and SP phases are about 90 deg out of phase, making it possible to sum the scaled radial and vertical components to suppress the S arrival and magnify the SP arrival. Beyond 54 deg, the IASP91 velocity model predicts

Figure 1. Raypath for SPmP (the SPdP phase resulting from the topside reflection from the Moho). S waves are shown as dashed lines, and P waves as solid lines.

Figure 2. Picking method:
 (a) three-component, low-passed seismogram showing the S and SPmP arrivals recorded at the CATO station; (b) radial and vertical components rotated by an angle so that the S arrival is primarily contained on the S trace and the SPmP arrival is seen on the P trace; (c) envelope functions of S and P traces to eliminate the effect of a phase shift of unknown magnitude occurring in the SPmP arrival; and (d) envelope functions aligned by eye to match the first swing of the S and P envelopes. (All traces have been normalized to unit amplitude.)

a precritical reflection for SPmP; thus, SP energy will begin sampling the upper mantle.

Our stack images P energy, following the moveout of SP, to distances of 62 deg. Energy of this magnitude is not seen in synthetics calculated for ranges beyond 55 deg in Earth models with crustal and upper-mantle velocities similar to IASP91, which does not contain an uppermost mantle discontinuity. These stacks are preliminary and require further analysis to assign significance to this feature.

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Figure 3. Crustal thickness estimates obtained at individual seismic stations.

Modeling Small-Scale Asthenosphere Convection under California

Principal Investigator: Jason Phipps Morgan (IGPP–Scripps Institution of Oceanography)

LLNL Collaborators: George Zandt and Charles Carrigan

Student: Mara Yale (UC Santa Cruz)

Abstract

We have performed a series of two-dimensional numerical experiments to study small-scale convection in the asthenosphere beneath California. Plate reconstructions in this region constrain the timing of the opening of a so-called slab window due to the northward migration of the Pacific–Juan de Fuca–North America Triple Junction. Regional seismic tomographic inversions provide a snapshot of the current thermal structure of the upper mantle beneath California, showing several seismically fast fingers that drip off from the lithospheric lid. Using the timing provided by the history of the opening of the slab window and knowledge of the current thermal state, our numerical experiments provide upper and lower bounds on the asthenosphere viscosity and demonstrate the effects of rheologies that depend on temperature, pressure, and strain rate.

Objectives

Our objective was to improve knowledge of asthenosphere properties under California by combining numerical modeling experiments with seismic data and tectonic reconstructions. We wanted to determine the effects of various physical parameters on the convective downwellings that have been imaged with seismic tomography in the asthenosphere under California. Spatial characteristics that are observed in tomographic images¹ include the aspect ratio of individual downwellings and the lateral spacing of the downwellings. The timing of the development of these instabilities is constrained by the depth of penetration and the known tectonic history, which fixes the timing of the initiation of the slab window. An additional constraint on the models is that the temperature contrast within the experimental downwellings must be large enough to be consistent with observed seismic velocity contrasts between the drips and the “ambient” asthenosphere.

Progress

In this project, we used a two-dimensional, finite-element model to perform numerical experiments. The model box is designed to mimic a vertical cross section running the length of California, 630 km long $\times$ 400 km deep. The initial temperature conditions define the lithosphere and the asthenosphere. Initially, temperature varies as a function of depth, such that within the lithosphere, there is a linear temperature gradient up to 800°C, and below the 800°C isotherm, the entire asthenosphere has an initial temperature of 1325°C (simulating hot asthenosphere filling in the slab window). The temperature of the top two rows of nodes within the asthenosphere are perturbed randomly with a 1% variation from 1325°C to seed the instability. Several rheologies were tested to determine the effects of a range of uniform viscosities, and how temperature, pressure, and strain-rate-dependent viscosity affect the downwellings.

In a series of uniform viscosity tests, we found the lithosphere to be 1000 times more viscous than the asthenosphere. A model with $\mu_{\text{asth}} = 10^{19} \text{ Pa} \cdot \text{s}$ and $\mu_{\text{lith}} = 10^{22} \text{ Pa} \cdot \text{s}$ results in downwellings that are consistent with those observed seismically in terms of both shape (aspect ratio) and timing. Downwellings reach approximately a 200-km depth in about 8 Ma. The temperature contrast is several hundred degrees, which is within the range that would be detected by a tomographic inversion. Models with both lithosphere and asthenosphere viscosities that are higher than the preferred model result in downwellings that are significantly wider than those observed seismically, and they take more than 30 Ma to reach 200-km depth. Decreasing both lithosphere and asthenosphere viscosities by an order of magnitude from the preferred model results in very narrow downwellings that reach 20-km depth in less than 2 Ma. This series of runs bounds the viscosity of the upper mantle to be about $10^{19} \text{ Pa} \cdot \text{s}$, which is consistent with postglacial rebound estimates of the upper-mantle viscosity in the western United States.

We incorporated more realistic rheologies in the numerical modeling by using experimentally derived parameters for flow laws.² In the upper mantle, two deformation mechanisms are likely to be important—Newtonian diffusion creep and non-Newtonian dislocation creep. Both mechanisms are temperature- and pressure-dependent. Thus, for the initial temperature field used, the viscosity is high in the lithosphere and lowest at the lithosphere–asthenosphere boundary; it increases with depth as the pressure dependence dominates. Dislocation creep depends on stress in addition to temperature and pressure. As asthenosphere blobs develop within either regime, the core of the blobs is colder and thus has a higher viscosity than adjacent material. The effect of the increasing viscosity with depth is to make the blobs flatten or mushroom out from their initial width. To allow the numerical model to include both deformation mechanisms, we must treat diffusion and dislocation creep as a pair of dashpots in series. The mechanism that gives the highest strain rate dominates creep. If stresses are small, then the dislocation creep viscosity will be large, and diffusion creep will dominate. Increasing the grain size increases the diffusion creep viscosity without changing the dislocation creep viscosity.

In our explorations of parameter space, we discovered that the grain size must be small enough (nominally $<10 \text{ mm}$) so that the viscosity of the upper mantle will be low enough for blobs to begin to grow. Once the blobs are initiated, if the amount of downwelling material is insufficient to create large stresses, diffusion creep will continue to be the dominant mechanism. If the stresses are large enough to make the dislocation creep viscosity significantly lower than the diffusion creep in some parts of the model box, the blobs will be affected by the strain. The state of stress created by the downwellings combines with the thermal state to determine the viscosity. Comparing a model run that allows dislocation creep in addition to diffusion creep to one that includes only diffusion creep reveals that dislocation creep makes the blobs pinch out more at the top of the asthenosphere. The morphology of the blobs at depth is also slightly different, because the blobs that form in the run of diffusion-plus-dislocation creep penetrate deeper than those in the diffusion-creep-only model where the blobs splay. Including dislocation creep increases the nonlinearity of the dynamics and thus facilitates the growth of the most dominant blobs. It is easier to keep going down in a channel that has already been formed than to initiate a new one.

Animations of the simulations reveal interesting interactions among the blobs. Initially, a flat-lying thermal boundary layer conductively grows into

the top of the asthenosphere. When this layer is thick enough to become unstable, downwelling develops. Although several blobs initially develop, two are usually slightly ahead of the rest. They continue to grow at the expense of the others. As one blob grows and sinks, it creates shear stresses along the base of the asthenosphere–lithosphere boundary, which inhibit the growth of adjacent downwellings.

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High-Field Strength and Rare-Earth Element Concentrations in Island-Arc and Continental Rifting Volcanic Rocks by Inductively Coupled Plasma Mass Spectrometry: Geochemical Constraints on Mantle Melting Processes

Principal Investigators: Charles E. Lesher and Miranda S. Fram (UC Davis)

LLNL Collaborators: Annie B. Kersting and Alan M. Volpe

Abstract

We measured trace-element and high-field-strength element (Nb, Ta, Zr, Hf) concentrations by inductively coupled plasma mass spectrometry (ICP-MS) in suites of primitive basalts from volcanoes from the Kamchatkan Arc and from the southeast Greenland volcanic rifted margin. The data were used in conjunction with various melting models to extract quantitative information about mantle melting processes in these two different tectonic setting. Our results for the southeast Greenland margin basalts delineate the relationship between continental extension and primary magma compositions and the role of a mantle thermal and chemical anomaly in melt production. The elements of the Kamchatkan Arc lavas ascribed to a dominantly mantle-derived origin, the high-field-strength elements (HFSEs) and the heavy rare-Earth elements (HREEs), form a trend comparable to the mid-ocean ridge basalt (MORB) values, at similar to slightly lower levels than MORB. To first order, this pattern can be explained by simple melting with degrees of melting similar to or slightly higher than that of MORBs.

Objectives

Our goal was to use trace-element and HFSE concentrations to investigate mantle melting processes in island-arc and continental rift settings. These elements are important for understanding basalt genesis because their concentrations are principally controlled by partitioning between melts and residual solids during partial melting in the Earth's mantle. To carry out these studies, we needed a method to obtain high-quality data on incompatible element concentrations in primitive lavas. The low concentrations (0.1 to 10 ppm) were difficult to analyze accurately and efficiently by other techniques. Our goal was to develop and implement a procedure to routinely analyze samples with very low abundances of HFSE, rare-Earth elements (REE), and other incompatible trace elements by using ICP-MS.

Progress

We successfully developed a routine technique for preparing and analyzing low concentrations of REEs (La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, Lu), HFSEs (Y, Zr, Nb, Hf, Ta), and large-ion lithophile elements (LILEs, Rb, Sr, Ba, Pb, Th, U) in mafic volcanic rocks by ICP-MS. The techniques developed at LLNL were also implemented at UC Davis. Samples were prepared in a newly constructed clean laboratory facility in the UC Davis Geology Department, and the analysis procedure was implemented using the ICP-MS in the Pomology Department. Standard rock powders analyzed at

UC Davis are in excellent agreement with those measured at LLNL and with other published values.

In the first project investigating continental rifting, we focused on melt generation processes during the rifting of Greenland from Europe 60 million years ago. Specifically, we analyzed samples collected by drilling during Ocean Drilling Program Leg 152 on the southeast Greenland margin.¹ We examined a nearly flow-by-flow sampling of basalts and picrites from the upper series in Site 917A. This portion of the stratigraphy is correlated with the transition from continental to oceanic volcanism; that is, older units are significantly influenced by continental crust, and younger units are built on wholly oceanic crust.² Magma generation in continental rift settings is controlled by both the thermal and compositional features of the mantle and by the extensional history of the overlying continental lithosphere. Partitioning of HFSEs, REEs, and other trace elements between mantle and melt depends on residual mantle mineralogy; thus, the compositions of erupted magmas are highly sensitive to the depth and extent of melting.

The lava flows show a strong stratigraphic progression in many trace-element ratios. For example, Lu/Hf increases from 0.14 to 0.30, reflecting a progressive decrease in importance of residual garnet during mantle melting. Ratios such as Th/Pb, Nb/Zr, Nb/La, and La/Sm define two geochemical groups within the flows. The two groups interfinger, and the more “depleted” one (with lower ratios) disappears with time. Moreover, within each group, there is a smooth variation in incompatible element ratios that is correlated with the variation in Lu/Hf and appears to reflect a gradual transition to higher extents of melting.

To make quantitative estimates of source mantle composition and melting conditions, we compared the data to results of a polybaric mantle melting model. We revised the model of Fram and Leshner³ to include more recently published constraints on peridotite melting reactions and partition coefficients. The modeling suggests that the mantle source compositions necessary to produce the two groups correspond to sources such as those inferred for normal mid-ocean ridge basalts (the depleted group) and for one component of the modern Iceland anomaly. The modeling further indicates that melting began well within the garnet stability field, suggesting that a thermal anomaly is present—perhaps related to the Iceland plume—for the entire sequence. Finally, the gradual changes in trace-element ratios through the upper series are largely due to an increase in the mean extent of melting and concomitant decrease in the mean pressure of melting, which can be explained by rapid thinning of the continental lithosphere, allowing the mantle to upwell and thus melt over a greater interval. These results suggest that the thermal and chemical portions of the mantle anomaly are decoupled in time, and that the rate of lithospheric extension controls changes in primary magma compositions.

In the second project investigating mantle melting beneath island arcs, we focused on analyzing the most primitive rocks erupted because these samples are the least modified by crustal processes. We selected the Kamchatkan Arc because it has produced some of the most primitive basalts erupted in island-arc settings.⁴ Island-arc magma generation proceeds by fluxing of the mantle with fluids derived from the downgoing slab. The trace-element patterns of the erupted basaltic lavas depend on the conditions of melting in the mantle wedge but are also strongly overprinted by input from subduction-related fluids. To understand the melting behavior of the mantle wedge, we must examine those elements for which the subduction flux is negligible relative to mantle wedge contribution. By examining fluid-

immobile trace elements, particularly the HFSEs, we strive to see through this overprint to the underlying mantle melting systematics.

The Kamchatkan Arc data from five volcanoes were normalized to MORB to facilitate comparison of the relative contributions of the mantle and slab for the range of elements analyzed. The Kamchatkan lavas are characterized by LREE enrichments and slight HREE depletions compared to MORB. This general pattern is similar to other island arcs. A first-order observation is that almost all the incompatible elements resulting from a dominantly mantle-derived origin (HFSE and HREE) form a trend parallel to the MORB normalizing value, at similar to slightly lower levels. From our preliminary analysis, we conclude that the HFSE pattern is not a result of residual minor phases or amphibole in the wedge, because such phases would fractionate these elements and fractionation is not observed. In addition, this pattern does not require complex melt–residue interactions in the melting column. This pattern can be explained by simple melting at similar or slightly increased degrees of melting relative to MORB with an LREE enrichment due to fluid fluxing from the subducted slab. We are evaluating models to test this hypothesis. The Kamchatka data are less depleted than the Kermadec and New Britain arcs, yet similar to the Aleutian and Vanuatu arcs. We are continuing to study the possible controls on the contrasting signatures from different island arcs.

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Shear-Wave Velocity Structure beneath Central California from Surface-Wave Dispersion

Principal Investigator: Jiajun Zhang (UC Santa Cruz)

LLNL Collaborator: William R. Walter

Abstract

We used a new method to measure the incident-azimuth anomalies of surface waves recorded at several broadband stations in California from 15 large, shallow earthquakes that have occurred since 1988. This method is based on analysis of polarization state vectors, which are calculated analytically from three-component seismograms. The earthquakes were located within an arc distance of 90 deg from the stations and lie either on the great circle path connecting the Mount Hamilton (MHC) and Pasadena (PAS) stations or on another path connecting the Columbia College (CMB) and Goldston (GSC) stations. The first path (MHC-PAS) is near the San Andreas Fault System (SAFS), and the second path (CMB-GSC) traverses the Sierra Nevada Batholith and the Basin and Range, parallel and to the east of SAFS. We observed strong incident-azimuth anomalies for Rayleigh waves with periods between 20 and 150 s. The anomalies were as large as 35 deg for a period of 30 s and 20 deg for a period of 150 s; however, the largest anomaly for Love waves with periods between 30 and 150 s is only 20 deg.

Objectives

Our goal was to use broadband surface-wave dispersion analysis to study earth structure and anisotropy in California and thus better understand the processes associated with the evolution of the Pacific–North American plate boundary. Surface-wave velocities strongly correlate with the age of the oceanic lithosphere and asthenosphere, with velocities for a young ocean being significantly reduced. The methods currently used in surface-wave dispersion analysis are applicable to regions with smooth velocity variations, but they are inadequate for regions encompassing strong lateral heterogeneities. The crust and upper mantle beneath California is highly heterogeneous, since it encompasses the active SAFS. Our objective is to develop new techniques for analyzing dispersion characteristics of waves propagating in laterally heterogeneous media. These techniques include a polarization analysis method and a high-resolution, two-station method of dispersion analysis.

Progress

We analyzed a data set of broadband seismograms from 15 large, shallow earthquakes that have occurred since 1988 along the northern and eastern Pacific, recorded by several broadband stations in California. These stations include stations Mount Hamilton (MHC), Pasadena (PAS), Columbia College (CMB), and Goldston (GSC) (Figure 1a).

We determined incident-azimuth anomalies of Rayleigh and Love waves as a function of instantaneous periods using the method of pure-state polarization analysis, which is based on state vectors of three-component seismograms.¹ Mode contaminations were corrected using synthetic seismograms computed for the laterally homogeneous Earth model PREM following the procedure of Gilbert and Dziewonski.² For both Rayleigh and Love waves with periods between 20 and 150 s, the errors for the measured

Figure 1. (a) Mercator projection of the northern and eastern Pacific and the locations of stations (triangles) and earthquakes (plus signs) used in this study. Source-receiver great-circle (GC) paths (solid lines) are shown for station PAS to three events. Incident-azimuth anomalies versus instantaneous periods for Rayleigh (thick lines) and Love (thin lines) waves recorded at the stations from (b) the March 8, 1991, eastern Siberia earthquake and (c) the May 13, 1993, Alaska Peninsula earthquake. Azimuth anomalies are measured from the great circle between source and station using polarization state vectors of ground displacements.

azimuth anomalies corrected for modes contaminations are, in general, less than 10 deg.

The incident-azimuth anomalies of Rayleigh and Love waves determined using this method are consistent for various earthquakes in close distances (Figures 1b and 1c). Our results indicate that this method provides a useful tool to study the refraction of surface waves propagating along the circum-Pacific.

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2. Gilbert, F., and A. M. Dziewonski (1975), "An Application of Normal Mode Theory to the Retrieval of Structure Parameters and Source Mechanisms from Seismic Spectra," *Philos. Trans. R. Soc. London, Ser. A.* **278**, 187.

Section IV. IGPP–LLNL Seminars and Workshops

Center for Geosciences

Seminars

November 3, 1994

“Water, Water Everywhere, Not a Drop to Drink: Health Implications and Treatment Options for Arsenic in Drinking Water”

Janet Hering, UC Los Angeles

November 21, 1994

“High-Resolution Windows into Past Climate: The Coral Record”

Malcolm McCulloch, Australian National University, Canberra

December 1, 1994

“REE Mobility in Crustal Fluids”

K. Vala Ragnarsdottir, Department of Geology, University of Bristol

December 2, 1994

“Phase Relations of FeO and ReS at High Pressure”

Yingwei Fei, Carnegie Institute of Washington, Geophysical Laboratory

December 2, 1994

“Crystal Chemistry of Iron in Mantle Phases”

Catherine McCammon, Bayerisches Geoinstitute, Universtat Bayreuth

December 6, 1994

“Current Synroc Research at the Australian Nuclear Science and Technology Organization”

Katherine L. Smith, Australian Nuclear Science and Technology Organization (ANSTO)

December 9, 1994

“Successful In Situ Bioremediation at the Chico Municipal Airport”

Ken Jackson, LLNL

December 12, 1994

“Geochemical and Geophysical Results from the German Deep Drilling Project”

Johannes Stoll and Juergen Bigalke, University of Frankfurt, Germany

January 4, 1995

“Mechanisms of Shallow Magmatic Differentiation”

Alexander R. McBirney, Center for Volcanology, University of Oregon, Eugene

February 27, 1995

“Transformation of Aromatic Amines in Sediments Amended with Hydrogen Peroxide: Reaction Pathways”

Leah Matheson, Environmental Protection Agency Laboratory, Athens, GA

February 23, 1995

“Remediation of Organic Contaminants with Iron Metal: Processes Affecting Remediation Performance”

Paul G. Tratnyek, Department of Environmental Sciences and Engineering, Oregon Graduate Institute

February 23, 1995

“Application of U/Th Series Disequilibrium Concepts to Rock–Water Interaction Modeling”

Miro Ivanovich, Analytical Services, United Kingdom

February 28, 1995

“What Makes a Hot Spot Swell”

Jason P. Morgan, Scripps Institute of Oceanography, UC San Diego

March 9, 1995

“The Bonanza Arc, Vancouver Island, Canada: A Window into the Deep Crust of an Island Arc”

Susan Dabari, Geology Department, San Jose State University

March 31, 1995

“Massive Ignimbrites, Huge Calderas, Monstrous Lava Flows: The Products of Silicic Magmatism in the Central Andes”

Shanaka L. de Silva, Department of Geography and Geology, Indiana State University, Bloomington

April 12, 1995

“Fluid Inclusion Systematics of Geothermal Systems”

Joseph Moore, University of Utah

April 18, 1995

“Evaluation of a Genetically Engineered Model Organism for In Situ Bioremediation”

Rainer Erb, German National Center for Biotechnology

April 25, 1995

“Trace-Element Partitioning between Amphibole Phlogopite and Basanite Melt”

Thomas LaTourrette, Division of Geological and Planetary Sciences, California Institute of Technology

May 3, 1995

“Laboratory and Field Investigations of Remediation of PCP in Soil”

Ulrich Larsson, National Environmental Institute of Denmark

May 3, 1995

“The White Island, New Zealand, Scientific Drilling Project”

Wilfred A. Elders, Department of Earth Sciences, UC Riverside

May 30, 1995

“Metabolic Tolls for Generating Biocatalysts to Degrade Aromatic Pollutants”

Victor de Lorenzo, CSIC Institute, Madrid

June 8, 1995

“Physics Appreciation: A College Course for Non-Science Majors”

John White, LLNL

June 12, 1995

“Rapid Association of Regional Network Phases”

Carl Johnson, Geology Department, University of Hawaii

June 27, 1995

“Spatiotemporal Patterns in the Energy Release of Great Earthquakes”

Barbara Romanowicz, Geology and Geophysics Department, UC Berkeley

July 14, 1995

“Development of Biosorption Technology for Treatment of Uranium Contaminated Wastewater Ex Situ”

Brandlyn D. Faison, Chemical Technology Division, Oak Ridge National Laboratory, TN

July 21, 1995

“Quartz Reactivity: Controls of Solvent–Surface Interactions during Dissolution and Tensile Fracture Processes”

Patricia Dove, School of Earth and Atmospheric Sciences

Astrophysics Research Center

Workshop

January 13–15, 1995
Microlensing Workshop
Hosted by IGPP-LLNL

Seminars

October 7, 1994
“Relativistic Binary Neutron Star Coalescence”
Grant Mathews, LLNL

October 14, 1994
“The Great Crash of Comet Shoemaker-Levy 9 with Jupiter”
Imke de Pater, UC Berkeley

October 21, 1994
“Results from the Calan/Tololo Supernova Survey: The Observational
Diversity of Type Ia Events”
Nicholas B. Suntzeff, Cerro Tololo Inter-American Observatory

October 28, 1994
“Theory and High-Energy Observations of Be-Star/Pulsar System PSR
1259-63”
Marco Tavani, Columbia University, NY

November 4, 1994
“Ionization and Abundances of Intergalactic Gas”
David R. Tytler, UC San Diego

November 10, 1994
“Recent Problems in Nuclear Astrophysics”
Karl-Heinz Langanke, California Institute of Technology

November 11, 1994
“Gamma-Ray Burst Optical Counterparts Search Experiment (GROCSE)”
Hye-Sook Park, LLNL

November 18, 1994
“The Vela Remnants Observed with the Hubble Space Telescope: Evidence
of Shock Compression and R-Process Elements”
George Wallerstein, UC Berkeley

December 2, 1994
“The Frequency and Effect of T Tauri Companion Stars”
Andrea Gehz, UC Los Angeles

December 7, 1994
“Dusty Quasars”
Michael Drinkwater, Anglo-Australian Observatory

December 9, 1994

“Gamma Ray Pulsars”

Roger Romani, Stanford University

December 12, 1994

“Equation of State of Molten Basalt and Its Implications for Magma Dynamics”

Linda Rowan, Johnson Space Center, Houston, TX

December 15, 1994

“Radio-Emitting X-Ray Bullet Ejected by the Vela Supernova”

Richard Strom, UC Berkeley

December 16, 1994

“New Approaches to Radiation Transport Theory”

Mamikon A. Mnatsakanian, UC Davis

January 17, 1995

“Gamma-Ray Bursts and Cosmology”

Nemiroff, NASA, Goddard Space Flight Center, Greenbelt, MD

January 20, 1995

“Extreme Ultraviolet Observations of Accreting White Dwarfs”

Chris Mauche, LLNL

January 27, 1995

“Black Holes in 2+1 Dimensions”

Alan Steif, UC Davis

February 3, 1995

“Pseudomoment Stellar Dynamics: Shape of the Galactic Dark Halo”

Peter Amendt, LLNL

February 10, 1995

“The Future of Cosmic X-Ray Spectroscopy”

Simon Labov, LLNL

February 17, 1995

“GLAST: A Next-Generation Gamma-Ray Space Telescope”

Bill Atwood, Stanford Linear Accelerator Center

March 10, 1995

“South Pole Experiments”

Jeff Peterson, Carnegie Mellon University

March 17, 1995

“Double-Mode Cepheids in the Magellanic Clouds: Results from the MACHO Project”

Doug Welch, McMaster University, Ontario, Canada

March 24, 1995

“Rings of Fire: Thermonuclear Combustion of Accreted Fuel on Neutron Stars”

Lars Bildsten, UC Berkeley

March 31, 1995

“Extragalactic Eclipsing Binaries: Astrophysical Laboratories and Cosmic-Scale Distance Indicators”

Edward Guinan, Villanova University, Pennsylvania

April 7, 1995

“The Millimeter Wave Anisotropy Experiment (MAX)”

Paul L. Richards, UC Berkeley

April 14, 1995

“Adaptive Optics and Laser Guide Stars for Astronomy”

Claire Max, LLNL

April 21, 1995

“Starburst Galaxies and Superwinds”

Mat Lehnert, LLNL

April 28, 1995

“The CDMS Experiment: A Search for WIMPs Using Novel Cryogenic Detectors”

Thom Shutt, UC Berkeley

May 1, 1995

“Science Information Infrastructure and Science On-Line: A Mechanism for Bringing Cutting-Edge Research into the K–12 Classroom”

Isabel Hawkins, UC Berkeley

May 19, 1995

“A Large-Scale Dark-Matter Axion Search”

Karl Van Bibber, LLNL

May 26, 1995

“Microlensing and Halo Cold Dark Matter”

Michael Turner, University of Chicago and NASA, FNAL Astrophysics Institute

June 2, 1995

“Numerical Investigation of Generic Big Bangs”

Beverly Berger, Oakland University, MI

June 9, 1995

“Photon Bubble Instability and Accreting Neutron Stars”

Julianna Hsu, LLNL

June 16, 1995

“New Results on Low-Mass Star Theory: Implication for the Missing Mass in the Galaxy”

Giles Chabrier, Ecole Normale Supérieure, Lyon, France

June 23, 1995

“Looking for the Highest Energy Gamma Rays and Cosmic Rays”

Carl Akerlof, University of Michigan, Ann Arbor

June 30, 1995

“Group Properties of the Generalized Stokes Intensities for Multi-Element Standing Waves in a Cavity”

Larry November, National Optical Astronomy Observatories, Tucson, AZ

July 28, 1995

“Observation of Gamma-Ray Bursts by BATSE on the Compton Observatory”

Gerald J. Fishman, NASA, Marshall Space Flight Center, Huntsville, AL

August 11, 1995

“Relativistic Numerical Model for Binary Neutron Star Coalescence”

James R. Wilson, LLNL

August 25, 1995

“Big Bang Nucleosynthesis in Crisis”

Sidney Bludman, University of Pennsylvania, Philadelphia

October 27, 1995

“The Quest for Accretion Disks in Active Galaxies”

Michael Eracleous, UC Berkeley

November 3, 1995

“From Fast Pulsars to Strange Dwarfs”

Fridolin Weber, Lawrence Berkeley National Laboratory

November 10, 1995

“First Results from the VLA FIRST Survey”

Robert Becker, UC Davis and LLNL

November 17, 1995

“The Centers of Globular Clusters as Seen by Hubble Space Telescope’s WFPC2

Raja Guhathakurta, UC Santa Cruz

December 1, 1995

“Recent Theoretical and Observational Advances in the Study of Brown Dwarfs and Extra-Solar Giant Planets”

Adam Burrows, University of Arizona, Tucson

December 8, 1995

“Structure and Dynamics in the Central Sub-Parsec Region of the Galaxy NGC 4258”

Eyal Maoz, UC Berkeley

December 15, 1995

“Population Synthesis with a Library of Elliptical Galaxies”

Michael Gregg, LLNL

Section V. Bibliography

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Section VI. Fiscal Year 1996 IGPP–LLNL University Collaborative Research Program

Project No.	UC campus	Campus investigators	LLNL collaborators	Project title
AP 96-35	Santa Barbara	R. Antonucci, T. Hurt	W. van Breugel, A. Cimatti	Unified models and the alignment effect in radio galaxies and quasars
AP 96-38	Davis	R. H. Becker, G. Taylor	W. van Breugel	A VLA survey of the sky at 1400 MHz
AP 96-40	Berkeley	C. F. McKee, J. K. Truelove	R. I. Klein	Numerical studies of fragmentation in star-forming regions
AP 96-41	Berkeley	B. Sadoulet	C. A. Mears, S. Labov, M. Frank	A new technology for x-ray astrophysics and particle cosmology
GS 96-04	Berkeley	B. Romanowicz, D. Dreger, M. Antolik	S. Larsen	Three-dimensional modeling of regional broadband waveforms
GS 96-05	Berkeley	W. E. Dietrich, K. Nishiizumi, A. Heimsath	R. C. Finkel	Determination of a soil production law and its variation with long-term erosion rates using topographic data, measurement of soil depth, and cosmogenic nuclides
GS 96-07	Los Angeles	T. M. Harrison, A. Yin, X. Quidelleus	R. Ryerson	Crustal thickening in southern Tibet: The Renbu Zedong Thrust
GS 96-08	Los Angeles	A. Yin, P. Rumelhart	R. Ryerson, M. Caffee, R. Finkel	Structural and cosmogenic investigation of Quaternary slip rates along the left-slip Altyn Tagh Fault, central Asia
GS 96-10	Berkeley	T. McEvilly, R. M. Nadeau	L. Hutchings, W. Foxall	Recurrence, interaction, and source processes of small characteristic earthquakes
GS 96-11	Berkeley	B. L. Ingram	I. Hutcheon	Trace-metal concentrations in otoliths: Salmon differentiation in San Francisco Bay and Delta
GS 96-12	Berkeley	J. W. Kirchner, D. E. Granger	R. C. Finkel	Determining geomorphological and ecological controls of erosion rates in the Pacific Northwest Using cosmogenic isotopes in stream sediment

Project No.	UC campus	Campus investigators	LLNL collaborators	Project title
GS 96-18	Berkeley	R. Jeanloz, A. Kavner	W. Nellis	Kinetics of shock synthesis of Fe ₂ SiO ₄
GS 96-19	Los Angeles	D. Farber, K. D. McKeegan	R. Ryerson	The effect of pressure on oxygen and silicon diffusion in olivine
GS 96-20	Berkeley	L. Johnson, R. Amirkbekian	K. Mayeda	Study of seismic attenuation in northern California using BDSN data
GS 96-22	Santa Cruz	Y.-S. Zhang	H. J. Patton	Three-dimensional modeling of upper mantle structure beneath the western United States
GS 96-23	Santa Cruz	J. Revenaugh, C. Reasoner, J. Lawrence, M. Hagerty	W. R. Walter	Array studies of northern California crust and uppermost mantle
GS 96-26	San Diego	J. P. Morgan, M. Yale	S. Ruppert	Modeling lower crustal flow under the Sierra Nevada: Is ductile flow compatible with the observed relief, seismic structure, gravity, and crustal thickness?
GS 96-27	San Diego	S. Constable	J. Roberts	Surface diffusion and conduction in polycrystalline olivine rocks
GS 96-29	San Diego	P. Shearer, P. Earle	W. Walter	Imaging the 80-km discontinuity with shear-coupled P waves
GS 96-31	Santa Cruz	Q. Williams, C. Lundstrom	R. Ryerson	Experimental constraints on the transport of basaltic melt in Earth's mantle
GS 96-33	Davis	D. Leshner, D. Tinker	I. Hutcheon	Experimental determinations of O and Si self-diffusion in melts of Di–An–Ab compositions at high pressure