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Lithospheric Processes

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). Our main objective was to improve understanding of the origin and evolution of the Earth's lithosphere by studying selected processes, such as deformation and magmatic intrusion during crustal extension, formation and extraction of mantle melts, fluid transport of heat and mass, and surface processes that respond to deep-seated events. Additional objectives were to promote and develop innovative techniques and to support relevant educational endeavors. Our seismic studies suggest that underplating of crust by mantle melts is an important crustal-growth mechanism, that low-angle faults can be seismogenic, and that shear deformation creates mantle anisotropy near plate boundaries. Results of geochemical work determined that magmas from oceanic intraplate islands are derived from a uniform depth in the upper mantle, whereas melts erupted at mid-ocean ridges are mixed from a range of depths. We have determined the extent and style of fluid infiltration and trace-element distribution in natural magmatic systems, and, finally, investigated ^{21}Ne as a tool for dating of surficial materials.

Background and Research Objectives

The term "lithosphere" in *Lithospheric Processes* refers to the solid outer portion of the Earth, which in most areas is less than 200 km thick. The lithosphere underlying continents is comprised largely of relatively buoyant, silicon-rich rocks that are difficult or impossible to subduct by plate-tectonic processes. In some continental regions, the lithosphere preserves rocks as old as approximately 4 billion years, a period of time spanning most of the age of the Earth. In contrast, oceanic lithosphere, consisting of relatively dense, Mg- and Fe-rich rocks, is continually subducted and reformed by plate-tectonic processes and, as a result, is entirely younger than about 200 million years (c. 4 % of Earth's history). Beneath the lithosphere is a partially molten region of the upper mantle termed the "asthenosphere." It is the low-viscosity, low-shear-strength zone on which the tectonic plates move and from which magmas are ultimately derived. Movement of heat and fluids (including silicate melts) from the asthenosphere into the overlying lithosphere gives rise to much of the deformation and magmatism manifested at the Earth's surface. The lithosphere constitutes a thermal and mechanical boundary layer on the deeper, convecting portions of the Earth's mantle. Thus, the lithosphere incorporates a record of present and past dynamic processes involving the deeper mantle, possibly including its convective overturnings.

The scientific objective of this project was to derive a better understanding of the origin and evolution of the Earth's lithosphere, both the crustal and mantle component, and the underlying asthenosphere by studying selected major processes. Processes included (1) mechanisms, both tectonic and magmatic, of crustal extension, (2) formation and extraction from the mantle of magmas in different plate-tectonic settings, (3) tectonic deformation (plate-scale and smaller), (4) fluid flow and the resulting transport of heat and mass, and (5) surface processes such as sedimentation, erosion, and uplift, which are responses to deep-seated events.

A corollary objective of this project was to promote and/or develop innovative geochemical and geophysical techniques ("tools"), where appropriate, which are likely to have broad application to the study of lithospheric processes. Examples are the systematics of the U/Th and Th/Ra isotopic decay schemes, and the potential for certain cosmogenic isotopes such as ^{21}Ne to be useful in dating surficial materials.

Finally, support of relevant educational endeavors, where appropriate, continued to be an objective of this project.

Importance to LANL's Science and Technology Base and National R&D Needs

Research conducted under this project strongly relates to Laboratory and DOE core interests in several ways. First, our seismic studies have resulted in development of better numerical models for computing velocities of deep seismic waves, mainly P-waves. Seismic waves travel with different velocities depending primarily on intrinisic mineral and rock properties and temperature. Seismic velocities beneath stable, cold cratons such as the interior of North America or other continents are inherently faster than beneath orogenic areas such as the Western U. S., but lateral velocity differences exist on all scales. Detailed travel-time models are required for accurately locating and determining the magnitude of seismic events of either natural or anthropogenic origin. Our work has also resulted in an improved understanding of anisotropic velocity effects in the upper mantle beneath the Western U. S. Altogether, the regional models we have developed will improve ability to accurately locate seismic events worldwide, and thus contribute to the Laboratory's efforts in areas of nuclear nonproliferation and reducing the nuclear danger.

Results from this project in studying fluid flow have resulted in an improved understanding of heat and mass transfer resulting from fluid flow in natural systems. This work helps constrain equilibrium partition coefficients between minerals and fluids for certain elements, and provides information on heterogeneities in natural systems. These data will augment numerical models of fluid flow and transport, currently an active field of investigation at Los Alamos. Our work will have direct application in environmental restoration efforts.

Our work on cosmogenic isotopes, such as ^{21}Ne, is at the forefront of international research efforts on the use of cosmogenic nuclides for surface exposure dating. Such research uses the unique ultra-clean laboratories and mass-spectrometric facilities of Los Alamos and the expertise of Los Alamos staff. Surface-exposure dating using cosmogenic nuclides has application to numerous basic scientific and applied projects throughout the earth sciences, including areas in which Los Alamos has traditionally been involved. Potential applications include neotectonic studies, seismic hazards, and global climate studies on local to regional scales.

Scientific Approach and Accomplishments

We have adapted a multidisciplinary approach, using a combination of field- and laboratory-based studies and numerical modeling. For study of magmatic processes we have used a combination of (1) conventional field mapping, documentation, and sample collection techniques, (2) $^{40}Ar/^{39}Ar$ radiometric dating, (3) high-pressure rock-melting experiments, and (4) mass-spectrometric analysis of Rb-Sr, Nd-Sm, U-Th-Ra, and ^{21}Ne isotopes involving state-of-the-art mass spectrometers and ultra-clean laboratories. Our tectonic studies primarily involved analysis of seismic data from existing, large-scale nets such as the Southern California Seismographic Network, as well as collection of new data mainly using portable, field-based seismometers.

Studies of fluid flow involved a combination of field sampling, conventional major- and trace-element geochemical analysis, and ion- and proton-probe microanalysis of trace elements in mineral grains.

We have worked with collaborators, especially students, outside of Los Alamos wherever possible and appropriate. This approach augments and extends the expertise of Los Alamos staff members, promotes communication with universities, brings students and their faculty to Los Alamos, and is generally very cost-effective for us. An overriding criterion for collaborations in all cases is "good science."

Seismic studies in regions having undergone crustal extension show two important features: 1) the lower crust in such regions tends to be characterized by numerous parallel, subhorizontal reflective layers and 2) crustal thickness may be maintained independently of the amount of local extension. Interpretation of these features has been a major problem in understanding the process by which lithospheric extension occurs. Our studies of seismic Pn refracted waves in the central and southern Basin and Range province confirm with a high degree of confidence that the Moho (crust-mantle boundary) is flat under the southern Basin and Range province, independent of the amount of extensional deformation that affected the overlying crust. This result, which is not expected from purely rheological properties of crustal rocks, suggests that mantle-derived basaltic magmas have ponded at the Moho, a density interface, in a process called magmatic "underplating." Although underplating is still not well documented or understood, it is apparently an important mechanism by which growth of crust occurs in continental regions. "Ponding" (actually, intrusion of magma into sill-like bodies) may give rise to the observed seismic reflectors in the lower crust. Regarding strain mechanisms by which crustal extension occurs, our studies of the microseismicity of the upper and middle crust above a sill-like magma chamber in the central Rio Grande rift, New Mexico, lead us to conclude that low-angle listric or detachment faults can be seismogenic (i.e., capable of generating earthquakes), answering a question that has been controversial for many years.

Mantle seismic anisotropy is a direct indicator of mantle strain history, and thus constitutes an important tool in the study of tectonics. Seismic anisotropy results from the alignment of olivine grains during deformation of the mantle. We used data from the Northern California Seismic Network to determine the velocity variations, anisotropy, variations in anisotropy, and variations in crustal seismic delay times for northern California. Our results show, for example, that near the San Andreas fault system anisotropy is high (2-4 %) and oriented with the fast direction parallel to the fault. This observation suggests that simple shear strain has oriented the mantle material at the plate boundary. This deformation seems to be constrained to within 200 km of the San Andreas fault zone. We have also obtained new images of the mantle low-velocity zone beneath the Sierra Nevada Mountains. Despite the fact that the Sierra Nevada range contains the highest point in the lower 48 states (Mt. Whitney, 4419 m), the range seems not to be underlain by a thick crustal root. Rather, it is supported by a low-velocity (low-density) upper mantle.

From our Nd-Sm and U-Th-Ra isotopic studies of mantle-derived (basaltic) rocks from different plate settings, we have determined that melts from oceanic (intraplate) islands such as Hawaii are derived essentially from a single depth in the garnet-bearing upper mantle, whereas melts erupted at mid-ocean ridges are derived from a range of depths in the upper mantle (polybaric fractionation). Extraction of magmas from a range of depths -- and mixing of these melts with each other -- reflect the larger degree of partial melting, the larger volume of mantle affected, and the divergent plate motions that characterize mid-ocean ridges. Mixing of polybaric melts yields a distinct geochemical and isotopic signature that has been very difficult to interpret. The preservation of secular disequilibrium in all of these lavas allows us to conclude that they were extracted from their source regions and erupted to the surface within a short (<7000 years) period of time, i.e., were not held in crustal magma chambers for long periods of time. A better understanding of melting processes will help constrain upper mantle dynamics, including upwelling of deep portions of the mantle as plumes.

We have completed a series of laboratory rock-melting experiments on basaltic rocks from the Clear Lake region of California, which complement chemical analyses of these same rocks. The results document the general crystallization behavior of representative "primitive" (i.e., derived directly from the mantle without compositional modification) rocks, and allow us to conclude that fractionation of these melts began in the middle to lower crust. Such information will be important in understanding the origins of crustal rocks in this plate-margin setting.

From our studies of trace element variations in contact-metamorphosed siliceous dolomite, we have determined the extent and style of fluid infiltration around a small intrusion of magmatic rock. Although we investigated many elements, the elements Mn, Fe, Cr, and Cu in the country rock increase in concentration toward the intrusion, which implies infiltration of these elements from the magmatic fluid. Moreover, the distribution of these elements documents that fluid infiltration was highly heterogeneous, yet local equilibrium was maintained for at least Mn and Fe. This result is important because it allows calculated distribution coefficients of Mn between minerals to be used as a geothermometer. The heterogeneous infiltration determined by this field study would probably not be predicted by existing numerical models, and thus serves to complement such models.

From detailed stratigraphic profiles of local soils, measurements of ^{21}Ne in quartz obtained from the soils, and independent ^{14}C dating, we evaluated the use of ^{21}Ne, a cosmogenic isotope, as a tool for exposure dating and for determining rates of surface process such as denudation and aggradation. We showed that, with appropriate soil-stratigraphic data, cosmogenic techniques can be extended to depositional and soil-forming environments. We determined denudation rates for the Pajarito Plateau area of New Mexico of 6-16 cm/ka over the last 150 ka. These results have important applications to numerous basic and applied research problems.

Our field work in the Middle Awash region of the Ethiopian rift provided important data on the composition and timing of volcanism and on the style (i.e., explosive pyroclastic vs. passive lava flow) of eruption, providing a record that will be useful for interpretation of the detailed tectonic and magmatic evolution of the rift. This region of the Ethiopian rift, part of the larger East African rift system, is unique in that it is transitional between the continental part of the rift to the south and the mid-oceanic spreading system to the northeast. Our work has been the key for establishing that hominid remains found at this locality are the oldest (4.4 million years) yet found anywhere.

A book-writing project, "Continental Rifting: Evolution, Structure, and Tectonics," partially sponsored by this focus, came to successful conclusion last year (1995) with publication by Elsevier of a book by the same name. Results of several LDRD-sponsored projects were included therein. A summary and overview of continental rifts and rifting processes, this book has received good reviews by the geological community.

We co-sponsored a workshop titled, "The Secular Variations in the Production Rates of Cosmogenic Nuclides on Earth," which drew together 40 international scientists involved with problems of determining *in situ* production rates, paleomagnetism, nuclear cross sections, cosmic ray interactions, and other branches of geochronology.

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