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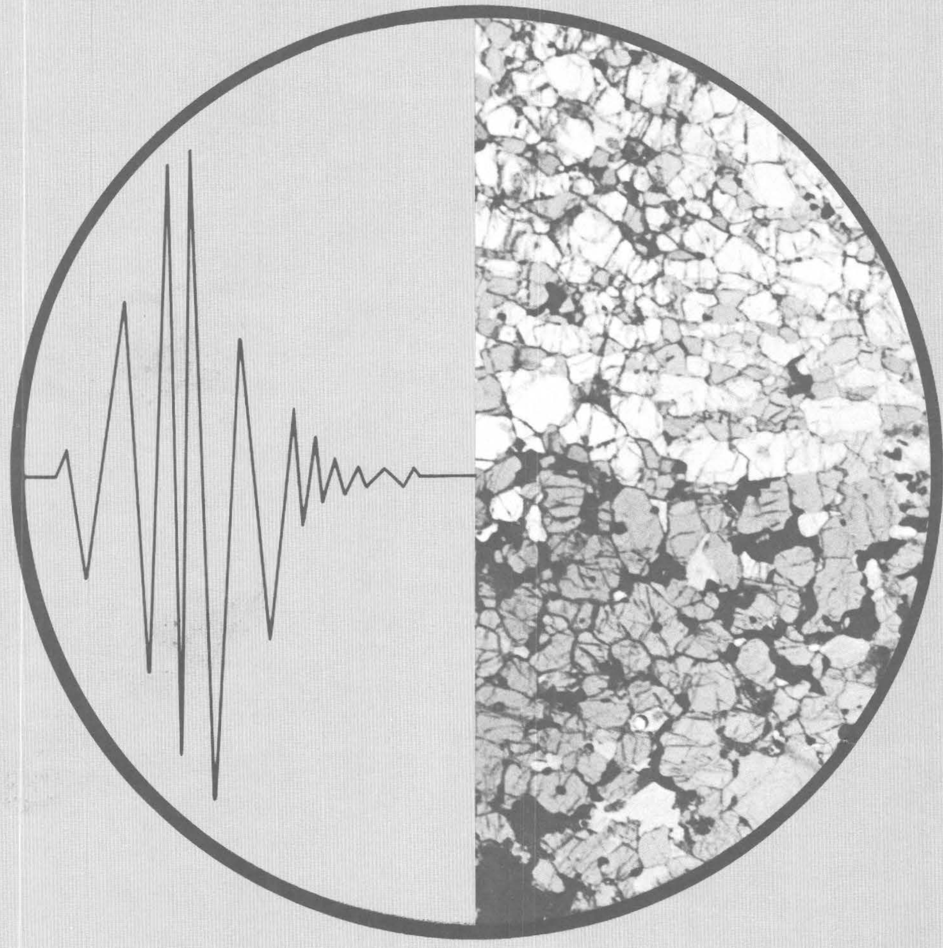
Geophysics and Petrology of the Deep Crust and Upper Mantle— A Workshop Sponsored by the U.S. Geological Survey and Stanford University



U.S. GEOLOGICAL SURVEY CIRCULAR 956

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Jay S. Noller, Stephen H. Kirby, *and* Jane E. Nielson-Pike, *Editors*

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CONTENTS

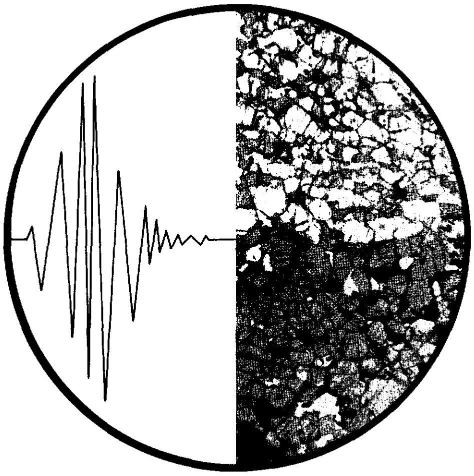
Page

Deformation, Preferred Orientation and Property Anisotropy in the Continental Lithosphere

Physical State and Processes of the Continental Lithosphere

Page

Introduction and Overviews



WORKSHOP OVERVIEW AND SUMMARY

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The extended abstracts collected here are the result of a workshop on the nature of the lower crust and uppermost mantle that was convened at Stanford University in January 1986 under the sponsorship of the U.S. Geological Survey (Deep Crustal Studies Program) and Stanford University (Department of Geophysics). The purpose of the workshop was to bring together for the first time leading scientists from some of the diverse disciplines that are represented in studies of the lower crust and uppermost mantle. Large and expensive consortia devoted to geophysical soundings, such as COCORP,[1] CALCRUST,[2] TACT,[3] and PACE[4] have revolutionized crustal research in the United States in the past 10 years. However, the structural, thermal, and magnetic models derived from these projects usually do not produce unique solutions, and they require more data about the chemical, mineralogical, and textural character of samples that represent the lower crust and upper mantle.

[1] Consortium for Continental Reflection Profiling
[2] Southern California Consortium for Crustal Studies (southern California)
[3] Trans-Alaska Crustal Transect (central Alaska)
[4] Pacific-Arizona Crustal Experiment (southern Basin and Range and southern California)

The earth scientists who participated in the workshop are engaged in research of the structure, state, petrology, composition, and evolution of the deep continental lithosphere. Each of the disciplines represented contributes significant data about the nature of the deep lithosphere, but each approach has limitations. For example, geophysical observations provide clues about the structure and state of the deep continental lithosphere, from large-scale seismic refraction and reflection surveys, heat-flow observations, and measurements of the Earth's magnetic and gravity fields. However, structural interpretations of these observations require assumptions about the petrology, composition, and physical properties of deep lithospheric materials. Petrological and geochemical studies of xenoliths and deep terranes, our most direct samples of the deep lithosphere, yield information about lithologies, mineral compositions, and in situ physical conditions of the deep lithosphere. However, xenoliths are modified compositionally by magma-forming processes, and also by decompression and alteration during their rapid ascent to the surface. Deep terranes also undergo reequilibration and alteration during slow emplacement within the crust. Field geological observations of exposed deep crustal and mantle terranes in regions of Neogene crust building can provide information about textures caused by deformation and reveal structural relationships among rock types at depth. However, the tectonic emplacement produces structural complexities that can obscure the evidence of crust-forming processes. Laboratory measurements of physical properties, such as elastic wave velocity (V_p, V_s), density, the stability of mineral assemblages, and rock rheology, all are crucial to modeling the constitution and thermomechanical evolution of the continental lithosphere. However, measurements are made on samples of limited size and over relatively short times, compared to the conditions of natural physical phenomena in the deep crust and uppermost mantle. Theoretical investigations of large-scale tectonic, thermal, and mass-transport processes, such as continental rifting and collision, flexure, plate-scale faulting, and large-scale plutonism and volcanism, offers the potential for understanding the evolution of the continental lithosphere. However, such models are based on assumptions about process and initial conditions; they can be improved by use of information derived from the other disciplines listed above. Given these limitations, it is clear that, once brought together, scientists from a variety of disciplines might help each other both to better constrain interpretations of the deep continental lithosphere and to focus research on areas and materials of greatest interest.

In this summary we want to highlight the main themes of the presentations and discussions, which focused on the processes that may govern the growth and subsequent modification of the continental crust, as deduced from geophysical and geological studies of the uppermost mantle and lower crust.

Mechanisms of crustal growth--The mechanisms by which the crust grows must be deduced from the structure and petrology of crustal rocks. At best, large-scale geophysical profiles provide defocused images of structure in the deep continental lithosphere. The most tightly constrained interpretations are from areas where detailed mapping allows the extrapolation to depth of structures that are exposed at the surface.

Presentations and discussions emphasized interpretations of regions where crustal growth has occurred since the Mesozoic or is active today, such as areas above subduction zones and regions of large-scale intraplate extension.

The diverse nature of the crust-mantle boundary--Many presentations and discussions focused both on the nature of the crust-mantle boundary and on the definition of the Moho in the context of variable boundary structure and composition. It is clear that the idealized Moho, a stepwise change in composition or mineralogy, represented by a change in P-wave velocity from 6-7 km/s to greater than 8 km/s, is an inadequate description of the crust-mantle boundary in areas of active crustal formation. Examples of a laminated or gradational crust-mantle boundary are suggested by the petrology and geochemistry of xenoliths from Australia and the southwestern United States, and from structural and petrological studies of deep terranes in Alaska, Wyoming, and the Ivrea Zone of southern Europe. P-wave velocities in some of these areas may reflect magmatic processes, the related effects of a steep geothermal gradient, and (or) metamorphic reactions. The crust-mantle boundary in regions of recent crustal extension may be a young feature, with depth influenced by magmatic or metamorphic processes. In discussions seismologists emphasized that the term "Moho" (Mohorovicic discontinuity) should be reserved for the description of the Earth's velocity distribution based on seismic observations, and not used as a synonym for a crust-mantle boundary based on petrological or other criteria.

The origin of deep flat-lying crustal reflectors--Deep subhorizontal reflectors are found in many large-scale seismic reflection profiles. These reflections commonly are abundant in the lower crust and absent below the Moho. The generation of these structures may be closely related to crustal growth and formation of the crust-mantle boundary. In discussions, proposed explanations for these structures included zones of planar mafic intrusions, metamorphic segregation, tectonic juxtaposition of unrelated terranes, and preferred orientation anisotropy developed in deep shear zones. Data from many disciplines support a zone of multiple mafic intrusions as the cause of many of the reflecting horizons, especially in regions of crustal extension, where dike injection probably is part of crustal growth processes. The positive buoyancy of mafic magmas in the mantle should provide a strong driving force for their segregation into the lower crust.

Seismic anisotropy and its implications for the flow and stress state of the crust and upper mantle--The physical properties of most rock-forming minerals vary with crystallographic direction, and this anisotropy extends to rocks if the mineral components have crystallographic preferred orientations. Metamorphic rocks may acquire preferred mineral orientation during plastic deformation at depth. A consequence of anisotropy can be large-scale azimuthal variations in elastic wave velocity, observed in the oceanic lithosphere and in the uppermost mantle under continents. These observations offer the exciting possibility of mapping the flow fields in the crust and mantle from seismic observations. Discussion addressed theoretical relations between the state of stress, the flow field, the resulting preferred orientations and anisotropies, and also the tectonic interpretations of P_n anisotropies in the uppermost mantle of the continents.

Fluids in the deep lithosphere--From determinations of their stable isotopes, the waters released in volcanic eruptions are meteoric or of metamorphic origin from relatively shallow depths. Except for CO_2, dry volcanic gases contain species produced by single-stage or multistage reactions between crustal or surface waters and silicic magmas. Estimations of the Earth's CO_2 budget also point to a significant deep crustal and (or) mantle reservoir, and studies of microstructures in mantle xenoliths demonstrate the presence of CO_2 in the deep lithosphere. Work on volatiles in xenoliths and rocks of the deep lithosphere is difficult because overprinted effects of near-surface alterations must be identified and deleted. Fuller knowledge of the abundance and composition of volatiles is crucial to understanding the physical properties of the deep continental lithosphere.

RECOMMENDATIONS

- Large-scale geophysical profiling consortia should call upon as much geophysical, geological, and petrological data as possible. Profile and deep drill-hole site selections should be guided by nearness to exposures of deep lithospheric terranes or to xenolith localities. Geologic mapping and petrological, geochemical, and physical properties studies of relevant materials should be part of the geophysical programs. Petrological and geochemical studies should focus on materials and sites that have the greatest geophysical significance.
- Xenoliths and rocks of exposed deep terranes should be the objects of multidisciplinary, collaborative studies. Xenolith studies should include characterizations of localities by statistical population counts. Laboratory studies should include mineral compositions, proportions, textures, and preferred orientations, whole-rock major- and trace-element compositions, mineral isotopic compositions, and bulk physical properties such as density, magnetic properties, and elastic and inelastic mechanical properties. Complete data of the sorts listed are most valuable when all are acquired on the same samples; however, sample size is a limiting factor.
- Systematic studies are needed of the effects of compositional variations (including major and minor elements and fluid proportions) on a range of physical properties and on composition-based geothermometers and barometers. Also, determinations of cation diffusion rates in pyroxenes are needed to evaluate the extent to which minerals will reequilibrate in response to changes in pressure, temperature, and composition. These, and allied microstructural studies, can aid in defining the effect of alteration in near-surface environments.
- Seismic techniques aimed at determining the fine structure of the lower crust and upper mantle are needed. These techniques include high-resolution reflection profiles that use closer seismometer and shot spacings, and interpretations of reflected arrivals using the spectral response of model structures, as exemplified by the CALCRUST experiments reported in this workshop.
- Experiments should be mounted to test the possibility that velocity anisotropies due to mineral preferred orientations cause enhanced

reflectivity in flat-lying shear zones. In a simple shear setting, mineral preferred orientations typically have a symmetry related to the shear direction and shear plane. If anisotropy at depth causes flat-lying reflections, the reflectivity should vary with the azimuth of the profile. This should not be the case if the velocity contrasts and reflectivity of laminated structures are isotropic.

- Geophysicists and geophysical consortia should maintain contact with those investigating chemical, petrological, laboratory, and theoretical aspects of deep continental materials. Future meetings, such as this workshop, can facilitate interdisciplinary communications.

CHARACTER OF THE LOWER LITHOSPHERE: LITHOLOGY

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The lower lithosphere comprises lower crust and upper mantle between about 20 and 100 km depth under continents, and shallower depths under oceans. Direct evidence of the lithologic character of the lower lithosphere is derived from study of ophiolites, which represent oceanic crust and mantle, exposed lower continental crustal sections and associated peridotite massifs, and xenoliths in volcanic rocks, which represent both oceanic and continental lithosphere. All of these occurrences are fragmented, and represent varied igneous, metamorphic, and tectonic histories.

The basis for describing the lithology of these rocks is not uniform, and commonly reflects the special focus of authors on one or another of these occurrences. This in turn obscures the similarities in range of lithologies, and, more importantly, the structural relationships among them. Table 1 lists the common rock types in a way that emphasizes the overlap--and differences--among the different modes of occurrence; that is, by omitting special place names that are not in common use and do not convey the mineralogy of the rocks, and omitting names that are acronyms.

Peridotite is the dominant mantle component of all occurrences. Important differences among the peridotites are mainly reflected in the nature of the aluminous phase (plagioclase, spinel, or garnet) and in the proportion of clinopyroxene present (<3-5 pct in harzburgite, >3-5 pct in lherzolite). Occurrences of peridotites with different aluminous phases in xenolith suites have been calibrated by experimental work. This has led to the generally accepted hypothesis that the upper mantle is mineralogically stratified. Plagioclase peridotite represents the shallowest (<0.9-1.1 GPa) and garnet peridotite is the deepest (>2.0-2.5 GPa) accessible mantle level. Variations in amount of modal clinopyroxene are thought to be related to varying degrees of partial melting, which in turn may reflect geodynamic environment of formation (Nicolas, in press). However, reenrichment of depleted peridotite may occur by melt infiltration in a variety of tectonic settings (Hamilton, 1981; Nicolas, in press) and by metasomatic processes (Wilshire, in press). Minor mafic lithologies commonly occur as inclusions in volcanic rocks and interleaved within the peridotites of massifs. These include spinel, garnet, and plagioclase pyroxenites, rocks rich in hydrous phases, gabbro, and their metamorphic equivalents; eclogite is found rarely in peridotite inclusions in kimberlite.

The lower crustal component of these occurrences is very diverse. In ophiolites it is dominantly gabbroic, and in continental settings it varies from dominantly silicic granulite of possible supracrustal paragenesis to mafic granulite formed by metamorphism of mafic intrusions from the mantle (Fountain and Salisbury, 1981; Hamilton, 1981); inclusion assemblages in volcanic rocks commonly contain gabbro or metagabbro or both. Less abundant lithologies include dunite, pyroxenite, and wehrlite at the base of feldspathic rock sections in ophiolites and eclogite, charnockite, and anorthosite in continental magmatic arc settings.

An important observation regarding the minor lithologies that occur in peridotite is that they duplicate the lower crustal section in ophiolites and alpine massifs. The origin of these minor rock types is controversial, but it is of vital importance in using inclusion assemblages in volcanic rocks as guides to the lithology and thermal structure of the lithosphere. The interpretation of these minor rock types varies according to their mode of occurrence. For example, gabbro bodies in massifs are clearly dikes, but as xenoliths they are interpreted either as cognate precipitates from the host lavas or as unrelated fragments of the crust. Although gabbro dikes in massifs are commonly recrystallized, granulite xenoliths are almost universally ascribed to lower crustal strata. Similar dichotomies apply to pyroxenite, eclogite, and wehrlite, and in certain instances, even to peridotite.

Integration of observations on the structural relationships of minor lithologies and peridotite in massif and xenolith occurrences (see Wilshire, in press, for review) indicates that the minor lithologies in both occurrences are dikes, and that they were emplaced in peridotite in a chronological sequence trending from higher to lower pressure. That is, partial melting and dike emplacement occurred sequentially in a rising peridotite diapir. The dike rocks so formed do not represent laterally continuous "strata" in the mantle or crust, but may be mineralogically (and texturally) identical to such "strata." Paleogeotherms reconstructed from such assemblages (to the extent that the currently available geobarometers are truly accurate) may represent the trajectory of a diapir and not a regional thermal structure of the lithosphere.

REFERENCES CITED

Fountain, D.M., and Salisbury, M.H., 1981, Exposed cross-sections through the continental crust: Implications for crustal structure, petrology, and evolution: Earth and Planetary Science Letters, v. 56, p. 263-277.

Hamilton, Warren, 1981, Crustal evolution by arc magmatism: Philosophical Transactions of the Royal Society of London, A, v. 301, p. 279-291.

Nicolas, A., in press, Structure and petrology of peridotites: Clues to their geodynamic environment: Reviews of Geophysics.

Wilshire, H.G., in press, A model of mantle metasomatism, in Mullen, E.D., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Boulder, Colo., Geological Society of America Special Paper 215.

TABLE 1. *Comparison of lower lithospheric lithologies in xenolith and massif occurrences*

[Group classification from Wilshire (in press). Overall relative abundances indicated by: all capital letters, abundant; lower cases letters, less abundant]

Group	Ultramafic lithologies	Anhydrous mafic/silicic lithologies	Hydrous lithologies
		OPHIOLITES	
Cr-diopside	HARZBURGITE Dunite Wehrlite	Clinopyroxenite	Hornblende wehrlite
Al-augite	- -	- -	- -
Gabbro/meta-gabbro	- -	GABBRO Plagiogranite	Hornblende gabbro
		ALPINE MASSIFS	
Garnetiferous ultramafic	Garnet lherzolite	Garnet websterite	Phlogopite peridotite Phlogopite pyroxenite
Cr-diopside	SPINEL LHERZOLITE SPINEL HARZBURGITE Dunite	Spinel clinopyroxenite Spinel websterite Spinel orthopyroxenite Garnet-spinel clinopyroxenite	- -
Al-augite	Spinel lherzolite	Spinel clinopyroxenite Spinel websterite	Kaersutite peridotite Kaersutite pyroxenite Kaersutite hornblendite Fe-Ti glimmerite
Gabbro/meta-gabbro	- -	2 Px gabbro 2 Px metagabbro Hornblendite Garnet-sillimanite granulite Charnockite Anorthosite Plagiogranite	2 Px hornblende meta-gabbro
		XENOLITHS IN BASALTS	
Garnetiferous ultramafic	Garnet lherzolite Garnet-spinel lherzolite	Garnet clinopyroxenite	Phlogopite lherzolite Phlogopite pyroxenite Mg-Cr glimmerite
Cr-diopside	SPINEL LHERZOLITE Spinel harzburgite Spinel dunite	Spinel clinopyroxenite Spinel websterite Spinel orthopyroxenite Garnet-spinel pyroxenite	- -
Al-augite	Spinel lherzolite Spinel wehrlite	Spinel clinopyroxenite Spinel websterite	Phlogopite pyroxenite Phlogopite lherzolite Kaersutite pyroxenite Fe-Ti glimmerite Kaersutite hornblendite
Feldspathic ultramafic	Feldspathic lherzolite	Feldspathic garnet clinopyroxenite Feldspathic clinopyroxenite Feldspathic websterite	- -
Gabbro/meta-gabbro	- -	2 PX GABBRO Olivine gabbro 2 PX METAGABBRO 2 PX GARNET GRANULITE Garnet-spinel granulite Charnockite Anorthosite	2 Px hornblende gabbro Hornblende metagabbro Amphibolite
		XENOLITHS IN KIMBERLITES	
Garnetiferous ultramafic	GARNET HARZBURGITE Garnet-spinel lherzolite Garnet-spinel harzburgite	Garnet clinopyroxenite Garnet websterite, eclogite	Phlogopite harzburgite Mg-Cr glimmerite Richterite peridotite Richterite hornblendite
Cr-diopside	Spinel lherzolite	- - - -	
Feldspathic ultramafic	- -	Feldspathic garnet clinopyroxenite	
Gabbro/meta-gabbro	- -	2 Px garnet granulite 2 Px granulite	- -

CHARACTER OF THE LOWER LITHOSPHERE: COMPOSITION

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Direct evidence of the composition of lower lithosphere is derived from the study of xenolith suites, ophiolites, and tectonic exposures of deep terranes that include alpine peridotite massifs and granulite-facies metamorphic rocks (Wyllie, 1967). Indirect evidence comes from the compositions of lavas derived from mantle and deep-crustal areas.

Mantle lithosphere (peridotite) is refractory and rich in Mg, Fe, and Si, with lesser abundances of Ca, Cr, and Ni. Compared to averages of crustal rocks, dominant mantle is poor in "incompatible" elements (those that preferentially enter a melt), which include K, Rb, Ba, U, Th, and the light rare-earth elements (LREE) (Jagoutz and others, 1979; BVSP, 1981). The LREE are depleted relative to heavy rare-earth elements (HREE) and relative to chondrite abundances. Also, compared to crustal values, the isotopic ratios of Sr and Pb, daughter products of the incompatible elements K, U, and Th, are low in abundance, and those of Nd, daughter of the compatible element Sm, are high (Menzies, 1983). Lavas with analogous compositional characteristics are judged to be of mantle origin. In general, peridotite richer in clinopyroxene also is relatively richer in the incompatible elements (Frey, 1984). These compositional characteristics are taken to indicate that variable amounts of melting and melt extraction removed clinopyroxene from mantle peridotite during and after early crust formation (Morgan and others, 1980; 1981).

The compositions of Mg-Cr-rich spinel-peridotite xenoliths from basalt, found worldwide, have greater chemical variability than do peridotites of the other occurrences (Frey, 1984). In some xenolith suites, clinopyroxene-poor peridotite is enriched in incompatible elements and in LREE relative to HREE (LREE/HREE). Isotopic ratios of Sr and Nd are widely variable (Menzies, 1983) and many of these samples lie nearer "bulk Earth" (and crustal) values than does depleted peridotite from massifs (Frey and others, 1985). Clinopyroxenes of some clinopyroxene-poor peridotite xenoliths also show the paradoxical depletion of incompatible major elements and relative enrichment of incompatible minor and trace elements (Kempton and others, 1984). Most explanations propose that these rocks underwent two events: depletion by melting, and a later metasomatic reenrichment (Frey, 1984; Dawson, 1984; Roden and Murthy, 1985).

Controversy about mantle metasomatism centers around how, where, and when metasomatism occurred. A favored hypothesis is that metasomatism pervades mantle regions worldwide, and is a necessary precursor to the generation of alkali basalt magmas (Boettcher, 1984). The metasomatic agent is a tenuous fluid or a melt derived from a few percent of melting in deeper (perhaps primitive) mantle (Frey, 1984). A competing idea is that metasomatism is consequent to production of basaltic melts (Wilshire, in press), and occurs in magmatic belts; for example, beneath rift zones. Young (less than 200 Ma) metasomatism of peridotite wallrocks by mafic mantle intrusions has been demonstrated in field and petrologic studies of both xenoliths and massifs (Wilshire and others, 1980; Quick, 1981). Recent interpretations of Nd-Sm model ages from samples identified as pervasively metasomatized suggest that the event was ancient (Archean) (Hawkesworth and others, 1983). The presence and composition of high-pressure megacrysts, particularly diamond, show other mantle chemical heterogeneities that apparently are ancient, but of poorly understood origins (Richardson and others, 1984).

The minor mantle lithologies are dominantly mafic (gabbroic or basaltic) compositions, with variable mantle isotopic ratios. Hydrous rock types of undisputed mantle origin (Varne and Graham, 1971) demonstrate that hydrous fluids exist in the mantle, although the rocks are differentiated and no longer have liquid compositions (Irving, 1980; Frey, 1984). These rocks may contain or be wholly composed of amphibole and (or) mica, with various accessory minerals, including apatite (Griffin and others, 1984). They have more K_2O and other incompatible trace elements, and enriched LREE/HREE, compared to anhydrous pyroxenites. CO_2-rich fluid inclusions in xenolith minerals are evidence for CO_2-bearing mantle fluids (Andersen and others, 1984). Controversy centers on whether mantle fluids are dominantly H_2O-rich or rich in H_2O and CO_2. Current research indicates that CO_2-rich fluids probably occur only in restricted portions of the upper mantle (Schneider and Eggler, 1984). Still unknown is the compositional range of mantle fluids, how mantle melts and fluids are produced and segregated, and how melts or fluids migrate through large volumes of solid rock.

Geochemical studies of crustal xenoliths were rare until recently. Crustal rock types are dominantly mafic rocks metamorphosed at granulite and amhibolite facies, but also found are more felsic types, such as pelitic gneiss and schist, quartzofeldspathic granulite, charnockite, and minor anorthosite. Mantle eclogite can be distinguished from much crustal eclogite by high contents of pyrope in garnet (Coleman and others, 1965). Trace-element and isotopic compositions of crustal xenoliths range from values like normal crust to the relatively depleted values characteristic of mantle rocks. Ages deduced from the isotopic systems are dominantly Precambrian, and are commonly interpreted as the ages of regional crust formation (Padovani and others, 1986). In some assemblages, compositional parameters are paradoxical and apparently indicate multistage depletion and enrichment during crustal formation (Esperanca, 1986).

The volume of deep lithosphere samples available for study is small, and the geochemical data set is even more restricted. For the suite of crustal xenoliths, interpretations of geochemistry are thought to be constrained by direct comparisons with exposed deep crustal terranes. In contrast, compositional variations of mantle xenolith suites are commonly considered to indicate that xenoliths are derived from mantle regions unlike those represented by exposed mantle terranes, such as ophiolites and peridotite massifs. New geochemical work on massifs may change this situation, because currently there are few data that can really be compared between peridotite of xenoliths and exposed terranes.

Present ideas of mantle composition and structure from xenoliths and basalt compositions suggest that "primitive" mantle exists at depth and is a chemical reservoir that has produced metasomatic agents since the Proterozoic. Primitive mantle is thought to have a major-element composition like "pyrolite" and REE abundances twice those of chondrites. Unfortunately, no known mantle rocks have primitive compositions. Isotopic variations of lavas are taken to indicate that a number of apparently discrete reservoirs have developed since formation of the primitive mantle. It is clear that chemical and physical inhomogeneities exist and may be related, although their scale and age are still unknown. Zindler and others (1984) have attempted to show how mantle heterogeneities may be preserved in a dynamic mantle.

REFERENCES CITED

Andersen, T., O'Reilly, S.Y., and Griffin, W.L., 1984, The trapped fluid phase in upper mantle xenoliths from Victoria, Australia: Implications for mantle metasomatism: Contributions to Mineralogy and Petrology, v. 88, p. 72-85.

Boettcher, A.L., 1984, The source regions of alkaline volcanoes, in Explosive volcanism: Inception, evolution, and hazards: Washington, D.C., National Academy of Sciences, p. 13-22.

BVSP (Basaltic Volcanism Study Project), 1980, Ultramafic xenoliths in terrestrial volcanics and mantle magmatic processes, in Basaltic volcanism on the terrestrial planets: New York, Pergamon, p. 282-310.

Coleman, R.G., Lee, D.E., Beatty, L.B., and Brannock, W.W., 1965, Eclogites and eclogites: Their differences and similarities: Geological Society of America Bulletin, v. 76, p. 483-508.

Dawson, J.B., 1984, Contrasting types of upper-mantle metasomatism?, in Kornprobst, J., ed., Kimberlites II. The mantle and crust-mantle relationships: Amsterdam, Elsevier, p. 289-294.

Esperanca, S., 1986, Lower crustal xenoliths from the Camp Creek locality, central Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 18, p. 105.

Frey, F.A., 1984, Rare earth element abundance in upper mantle rocks, in Henderson, P., ed., Rare earth element geochemistry: Developments in geochemistry 2: Amsterdam, Elsevier, p. 153-203.

Frey, F.A., Suen, C.J., and Stockman, H.W., 1985, The Ronda high temperature peridotite: Geochemistry and petrogenesis: Geochimica et Cosmochimica Acta, v. 49, p. 2469-2491.

Griffin, W.L., Wass, S.Y., and Hollis, J.D., 1984, Ultramafic xenoliths from Bullenmerri and Gnotuk maars, Victoria, Australia: Petrology of a sub-continental crust-mantle transition: Journal of Petrology, v. 25, p. 53-87.

Hawkesworth, C.J., Erlank, A.J., Marsh, J.S., Menzies, M.A., and van Calsteren, P., 1983, Evolution of the continental lithosphere: Evidence from volcanics and xenoliths in southern Africa, in Hawkesworth, C.J., and Norry, M.J., eds., Continental basalts and mantle xenoliths: Cheshire, Eng., Shiva Publishing, p. 111-138.

Irving, A.J., 1980, Petrology and geochemistry of composite ultramafic xenoliths in alkalic basalts and implications for magmatic processes within the mantle: American Journal of Science, Jackson Volume, v. 280-A, p. 389-426.

Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B., Lorenz, V., and Wanke, H., 1979, The abundances of major, minor, and trace elements in the earth's mantle as derived from primitive ultramafic nodules: Proceedings of the 10th Lunar and Planetary Science Conference, p. 2031-2050.

Kempton, P.D., Menzies, M.A., and Dungan, M.A., 1984, Petrography, petrology, and geochemistry of xenoliths and megacrysts from the Geronimo volcanic field, southeastern Arizona, in Kornprobst, J., ed., Kimberlites I: Kimberlites and related rocks: Amsterdam, Elsevier, p. 71-83.

Menzies, M., 1983, Mantle xenoliths in alkaline magmas: Evidence for mantle heterogeneity modified by magmatic activity, in Hawkesworth, C.J., and Norry, M.J., eds., Continental basalts and mantle xenoliths: Cheshire, Eng., Shiva Publishing, p. 92-110.

Morgan, J.W., Wandless, G.A., Petrie, R.K., and Irving, A.J., 1980, Composition of the earth's upper mantle - II: Volatile trace elements in ultramafic xenoliths: Proceedings of the 11th Lunar and Planetary Science Conference, p. 213-233.

_____ 1981, Composition of the earth's upper mantle - I: Siderophile trace elements in ultramafic nodules: Tectonophysics, v. 75, p. 233.

Padovani, E.R., Wandless, G.A., Reid, M., and Hart, S.R., 1986, Characterization of the deep crust in an active intracontinental rift: Evidence from xenoliths at Kilbourne Hole Maar [abs.]: Geological Society of America Abstracts with Programs, v. 18, p. 168.

Quick, J.E., 1981, Petrology and petrogenesis of the Trinity Peridotite, an upper mantle diapir in the eastern Klamath Mountains, northern California: Journal of Geophysical Research, v. 86, p. 11,837-11,863.

Richardson, S.H., Gurney, J.J., Erlank, A.J., and Harris, J.W., 1984, Origin of diamonds in old enriched mantle: Nature, v. 310, p. 198-202.

Roden, M.F., and Murthy, V.R., 1985, Mantle metasomatism: Annual Reviews of Earth and Planetary Sciences, v. 13, p. 269-296.

Schneider, M.E., and Eggler, D.H., 1984, Compositions of fluids in equilibrium with peridotite: Implications for alkaline magmatism-metasomatism, in Kornprobst, J., ed., Kimberlites I: Kimberlites and related rocks: Amsterdam, Elsevier, p. 383-394.

Varne, R., and Graham, A.L., 1971, Rare earth abundances in hornblende and clinopyroxene of a hornblende lherzolite xenolith: Implications for upper mantle fractionation processes: Earth and Planetary Science Letters, v. 13, 11-18.

Wilshire, H.G., in press, A model of mantle metasomatism, in Mullen, E.D., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Boulder, Colo., Geological Society of America Special Paper 215.

Wilshire, H.G., Pike, J.E.N., Meyer, C.E., and Schwarzman, E.C., 1980, Amphibole-rich veins in lherzolite xenoliths, Dish Hill and Deadman Lake, California: American Journal of Science, Jackson Volume, v. 280-A, p. 576-593.

Wyllie, P.J., ed., 1967, Ultramafic and related rocks: New York, Wiley, 464 p.

Zindler, A., Staudigel, H., and Batiza, R., 1984, Isotope and trace element geochemistry of young Pacific seamounts: Implications for the scale of upper mantle heterogeneity: Earth and Planetary Science Letters, v. 70, p. 175-195.

THE PHYSICAL STATE AND PROPERTIES OF THE CONTINENTAL LITHOSPHERE BASED ON XENOLITH STUDIES: AN OVERVIEW

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The deep-seated origin of the forces responsible for large-scale deformation of the continental lithosphere and the difficulty in extrapolating surface geological and geophysical observations to significant depth have motivated efforts to probe the deep continental lithosphere by various methods. The first is continental scientific drilling, both proposed and in progress. Second is large-scale geophysical profiling, such as seismic reflection and refraction surveys, aeromagnetic surveys, and gravity and electrical profiling. These efforts, which include integrated geological observations with sophisticated modeling studies, have revolutionized our understanding of the lower continental crust and uppermost mantle. Third is xenolith and deep terrane studies. Rocks of deep origin, brought up by volcanic eruptions or by uplift and erosion, presently represent our only samples of the lower crust and upper mantle. They present a challenge of interpretation because of the various ways they have been physically and chemically altered during their ascent to the surface and because their geologic context is poorly known, especially in the case of xenoliths. Nevertheless, as far as direct sampling below 15 km, they represent the only game in town.

Research on deep rocks can illuminate the deep lithosphere in a number of important ways: (1) They provide petrological and mineralogical information on rock types and distributions. Combined with direct laboratory measurements of their physical properties, their study provides powerful constraints on the models used to interpret the geophysical observations. (2) They give insights into the physical processes that operate in the deep lithosphere and that may have caused it to evolve into its present state. These insights stem from the structures and textures that are unique to the physical processes that are responsible for them. (3) There can be quantitative connections between the chemistries, textures, and structures on the one hand and the physical state of the lower lithosphere, such as the state of stress, temperature, and pressure. These connections come from laboratory studies of these features under controlled conditions. (4) Laboratory measurements of physical properties of deep rocks contribute not only in the first and third areas above but also provide basic information on the mechanical behavior of the continental lithosphere. For example, the flexure of the continental lithosphere depends on the depth distribution of plastic strength, and recent work suggests that the deep continental Moho represents a discontinuous increase in creep strength.

MICROSTRUCTURES IN MANTLE PERIDOTITES: ASTHENOSPHERIC/LITHOSPHERIC FLOW

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Microstructures in mantle peridotite (kimberlite and basalt xenoliths and various types of massifs) reflect different degrees of plastic deformation produced in different pressure-temperature conditions. These microstructures have been classified, and using petrofabric analysis and dislocation microstructure studies, it has been possible to show that they correspond in the majority of cases to a shear flow regime produced by dislocation creep.

A first-order problem is to distinguish among these microstructures those corresponding to an asthenospheric flow and those corresponding to a lithospheric one. An answer to this problem would have consequences on the general modeling of asthenosphere dynamics and on the interpretation of local mantle structures (asthenosphere diapirs or oceanic ridge structure, for example). An answer now seems possible provided that (1) one accepts that a signature of asthenospheric deformation is the presence of a basaltic melt within the deformed peridotite and (2) one is able to identify this situation in the now frozen peridotite structure. I present here evidence of the presence of such melts in various peridotite occurrences.

Harzburgite in ophiolitic massifs--This is the simplest situation in which the presence of melt during plastic flow of the upper harzburgite and dunite of the mantle section of ophiolites can be demonstrated (Nicolas and Prinzhofer, 1983). It can be seen in the field that gabbro dikes terminate into diffuse plagioclase-clinopyroxene impregnations in the peridotite. In the same area, such impregnations either are foliated along with the peridotite, proving that they penetrated the rock before or during the flow, or they are not deformed as much as the enclosing rocks, in which case the impregnation postdates the flowage. This proves the presence of melt during the plastic flow. Interestingly, the microstructure of these peridotites is a coarse mosaic. In dunite it mimics a magmatic accumulate structure. At this scale, the plastic deformation is only recorded by the olivine and enstatite fabrics which are, mainly the olivine one, remarkably strong. It is suggested that, due to the presence of a melt, grain boundary migration is greatly enhanced, resulting in a rapid consumption of crystals improperly oriented for slip, thus explaining the strong fabric as well as the development of a coarse-mosaic structure.

Plagioclase lherzolite from ophiolitic massif--In such massifs, exemplified by Lanzo (western Alps) and Trinity (Klamath Mountains) peridotites, the evidence of melt during plastic flow is given by field analysis. There, a complete sequence is followed from lherzolite in which the plagioclase is evenly distributed as dispersed aggregates parallel to the foliation, to small plagioclase-rich lenses formed by melt concentration parallel to the shear flow plane, and finally to gabbro dikes in a tension fracture orientation (Boudier and Nicolas, 1977). Outside the areas where this sequence is observed, it is difficult to ascertain whether the plagioclase aggregates parallel to the foliation in homogeneous plagioclase lherzolite represent melt pockets.

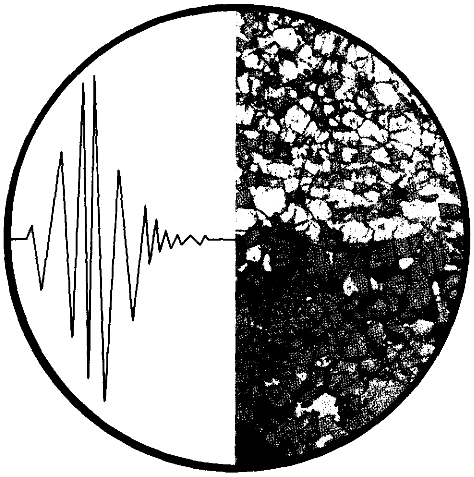
Spinel lherzolite xenoliths in basalt--It is proposed that the orthopyroxene-clinopyroxene spinel clusters, which are characteristic of the undeformed protogranular structure, crystallized from melt pockets in these lherzolites. It is now widely accepted that these clusters were derived from the garnets of garnet lherzolite, but the transformation is usually regarded as a subsolidus reaction. The evidence used to claim that the transformation proceeds by melting of the garnet and crystallization of the clusters from this melt is mainly indirect. In any case, the classical sequence of deformation described in these xenoliths affects these clusters. Thus, this deformation is at best contemporaneous with crystallization, and more probably subsequent to it, recording then lithospheric flow.

REFERENCES CITED

Boudier, F., and Nicolas, A., 1977, Structural controls on partial melting in the Lanzo peridotites, in Dick, H.J.B., ed., Magma genesis: Bulletin Oregon Department of Geology and Mineral Industries, v. 96, p. 63-78.

Nicolas, A., and Prinzhofer, A., 1983, Cumulative or residual origin for the transition zone in ophiolites: Structural evidence: Journal of Petrology, v. 24, p. 188-206.

Composition and Structure of the Continental Crust and the Upper Mantle



PETROLOGIC VARIABILITY OF THE OCEANIC UPPERMOST MANTLE

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Asthenosphere ascending between diverging lithospheric plates beneath an ocean ridge undergoes decompression melting. The melt is squeezed to the surface and erupts to form new crust over the ascending mantle. Peridotite dredged from the sea floor is likely to be the most depleted residue of this process. Because the degree of melting is linked to the depth of mantle upwelling, initial temperature, and chemistry, knowledge of the lateral chemical and mineralogic variability of residual mantle peridotite from the ocean ridges provides direct information on the process of mantle convection, as well as direct constraints on the generation of the spatially associated basalts.

EXPOSURE AND EMPLACEMENT

The large majority of abyssal peridotite has been recovered from the great oceanic fracture zones; smaller amounts have been dredged and drilled from rift mountains. At some fracture zones, areas exist where only altered peridotite and minor basalt have been dredged for thousands of square kilometers (see Bonatti and Honnorez, 1976). This is prima facie evidence that the flow of magma out of the mantle is not uniform, but is channeled away from fracture zones, erupting preferentially near the midpoints of adjacent ridge segments (Whitehead and others, 1984).

The exposure of abyssal peridotite is related to spreading rate. At the very slow spreading SW Indian and American-Antarctic Ridges (<1 cm/yr half rate) close to 67 percent of rocks dredged from fracture zones are altered mantle peridotite. At the slightly faster spreading Mid-Atlantic Ridge, fracture-zone dredge hauls contain 10-30 percent peridotite. At fast spreading ridges, like the East Pacific Rise, peridotite is rare. Emplacement clearly involves the diapiric ascent in the solid or partially molten state either to the base of the crust or, at some fracture zones, directly to the sea floor. Subsequent tectonism and faulting allow percolation of water into the peridotite, producing extensive hydrothermal alteration, principally serpentinization. In areas where the crust is thin (fracture zones) or the faults are large (median valley walls at slow spreading ridges) continued faulting allows the lower density serpentinite to work its way up through faults in the crust to the surface (Aumento and Loubat, 1971; Bonatti and Honnorez, 1976).

MINERALOGY

Modal analyses of 266 peridotite samples (570,740 points, 1 mm spacing) from 42 dredge hauls at 21 localities on 6 ocean ridges give an average of 74.8±5.3 percent olivine, 20.6±3.7 percent enstatite, 3.6±2.0 percent diopside, 0.5±0.2 percent chromian spinel, and 0.5±1.2 percent plagioclase. This is deceptive (note the standard deviation of plagioclase) as only 39 percent of these rocks contain plagioclase. Peridotite in most dredge hauls contains little or no plagioclase. Locally, there are areas where almost all dredged peridotite contains abundant plagioclase (up to 18 vol. pct.): at the Argo Fracture Zone, for example, peridotite in one dredge haul contained 3.1 percent plagioclase, while in another 9 km away there was none. This localized distribution of plagioclase is the same as in alpine peridotite bodies, where adjacent massifs in the same mountain belt contain either abundant or no plagioclase.

The proportions of minerals are not directly related to spreading rate. There is a relationship with proximity to mantle hot-spot regions: diopside-poor harzburgite, reflecting the highest degree of mantle melting beneath the ridge, occurs in greatest abundance in the vicinity of postulated mantle plumes (Dick and others, 1984, Michael and Bonatti, 1985). Along the American-Antarctic and SW Indian Ridges (spreading rates at 0.9 cm/yr), the average composition of dredged peridotite varies from lherzolite with 7.26 percent diopside at the Vulcan Fracture Zone far from the Bouvet hot spot, to harzburgite with 1 percent diopside at the Bouvet Fracture Zone.

Mineral compositions are very uniform, consistent with a residual origin. Enstatite is always close to saturation with respect to diopside, indicating that melting was restricted to the four-phase, two-pyroxene field (Dick and Fisher, 1984); this places an upper temperature limit on the mantle beneath ocean ridges. Exceptions are the alumina content of pyroxene and the Cr/(Cr+Al) ratio of spinel, which have large systematic variations with mineral proportions along the ocean ridges. Enstatite alumina varies from 6.0 to 2.0 weight percent, spinel Cr/(Cr+Al) from 0.160 to 0.525, and olivine ranges from $Fo_{90.0}$ to $Fo_{91.4}$, as the average modal proportion of olivine in the peridotite in the dredge hauls increases from

67 to 80 volume percent and diopside decreases from 5.9 to 0.2 volume percent. This is not expected in residues of fractional crystallization, where proportions are controlled by complex physical processes in magma chambers, whereas progressive changes in mineral compositions and proportions are anticipated in the residues of varying degrees of melting. Dick and others (1984) found that these variations in abyssal peridotite indicate a range from 10 to 30 percent melting.

Mineral compositions in plagioclase peridotite have more Ti-rich pyroxenes and more titanian and ferric spinels than does plagioclase-free peridotite. The spinels are notably similar to spinels in ocean-ridge basalts. Plagioclase (An_{68} to An_{98}) occurs in interstitial lenses, often in reaction relation with spinel, frequently with reverse zoning, with the most sodic plagioclase in the most plagioclase-rich rock.

BULK COMPOSITION

Primary bulk compositions of highly altered peridotite can be computed using the measured relict mineral compositions and modes. Such calculations indicate that, irrespective of degree of melting, both soda and titania amount to less than 0.02 weight percent in the plagioclase-free peridotite. Given the concentrations of these elements in basalt, this peridotite contains at best only 1 percent potential basalt, indicating that melt extraction was highly efficient in most areas of the abyssal upper mantle.

When the bulk compositions of the plagioclase peridotites are computed, however, they contain substantial soda and titania, which increase linearly with the proportion of plagioclase in the rock. This compositional variation can be modeled as a linear addition of abyssal basalt to residual plagioclase-free peridotite. Since both soda and titania are thought to behave as incompatible elements during melting, they should occur in negligible amounts in any residue, as we have found for the plagioclase-free peridotite. This, as can also be seen by numerical modeling, unequivocally rules out a residual origin for the plagioclase. The plagioclase-peridotite is best explained as hybrid rocks consisting of residual peridotite impregnated with trapped melt from which the plagioclase crystallized. The nonuniform distribution of plagioclase in abyssal peridotite, then, is additional evidence for localized flow of melt in the mantle, perhaps channeled by some form of gravitational instability (Whitehead and others, 1984).

On average, xenolith suites and subcontinental alpine peridotite (such as the Balmuccia and Baldissero peridotites) contain significant soda and titania in contrast to abyssal and ophiolitic alpine peridotites. Either they contain significant quantities of trapped melt (as does abyssal plagioclase peridotite), or they underwent little or no melting during their emplacement to the base of the crust. This may be the case for alpine peridotite emplaced from shallow lithosphere depths to the base of the crust during the initial stages of continental rifting.

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REFERENCES CITED

Aumento, F., and Loubat, H., 1971, The Mid-Atlantic Ridge near 45^{o}N. XVI. Serpentinized ultramafic intrusions: Canadian Journal of Earth Science, v. 8, p. 631-663.

Bonatti, E., and Honnorez, J., 1976, Sections of the earth's crust in the equatorial Atlantic: Journal of Geophysical Research, v. 81, p. 4101-4116.

Dick, H.J.B., and Fisher, R.L., 1984, Mineralogic studies of the residues of mantle melting: Abyssal and alpine-type peridotites, in Kornprobst, J., ed., Kimberlites II: The mantle and crust-mantle relationships: Amsterdam, Elsevier, p. 295-308

Dick, H.J.B., Fisher, R.L., and Bryan, W.B., 1984, Mineralogic variability of the uppermost mantle along mid-ocean ridges: Earth and Planetary Science Letters, v. 69, p. 88-106.

Michael, P.J., and Bonatti, E., 1985, Peridotite composition from the North Atlantic: regional and tectonic variations and implications for partial melting: Earth and Planetary Science Letters, v. 73, p. 91-104.

Whitehead, J., Dick, H.J.B., and Schouten, H., 1984, A mechanism for magmatic accretion under spreading centres: Nature, v. 312, p. 146-148.

THE XENOLITH MAGNETIC RECORD—TOWARD A BETTER UNDERSTANDING OF THE MAGNETIC STRUCTURE OF THE LITHOSPHERE

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The continental lithosphere emerges as an important study region for the 1980's. In this regard Magsat, launched by NASA, was timely and pioneering in that it has provided the impetus for considering the continental lithosphere as a magnetic material. However, to handle the Magsat anomalies requires that we consider the development of magnetization contrast in the context of crustal evolution. Rock magnetization data appropriate to this task are poorly developed or nonexistent. At the Goddard rock magnetism laboratory this problem is being addressed. Study materials were specifically chosen in order to address (1) the distribution of magnetic minerals and associated Curie points in the lithosphere, (2) the distribution of possible lithologies and their magnetic properties, and (3) the role of prograde and retrograde metamorphism in magnetic contrast development. Xenoliths, tectonically exposed crustal sections, and high metamorphic grade Precambrian terranes constitute the principal study materials.

Xenoliths are accidental fragments from any part of the upper mantle or crust traversed by the host volcanic rock and carried to the surface of the Earth. Xenoliths contain information about the magnetic minerals, level of magnetization associated with the minerals, and fundamental magnetic domain structure characteristics of otherwise inaccessible parts of the continental crust and upper mantle. In the ideal case with no decompression melt, no hydrothermal alterations, and no crack filling, the xenolith has thermoremanent magnetization characteristics appropriate to the included magnetic mineralogy and vector directions similar to the host. The Curie point, initial susceptibility, and magnetic domain structure are then characteristic in situ magnetic properties. The natural remanence measured in the laboratory is a thermoremanence and not therefore an indication of the in situ remanence. The remanence would have to be modeled in laboratory experiments at elevated temperature. I will discuss granulite grade and upper mantle xenoliths from the northeast and southwest Honshu arc (Japan), the Aleutians, Eastern Australia, the Colorado plateau and Rio Grande rift, and South Africa. I will summarize the magnetic contrasts across the crust-mantle boundary, as evidenced in the xenolith record, which supports the concept of the Moho as a magnetic boundary. Magnetic domain structure of the continental lithosphere will be considered using three separate data bases recently completed at Goddard. The xenolith data base will be contrasted with a surface crustal data base which includes all types of igneous and metamorphic rocks and a high-grade metamorphic rock data base which includes the Ivrea zone, the Kapuskasing zone, and granulite and amphibolite rocks from Norway, Scotland, Antarctica, and Minnesota. The magnetic domain structure is the basis for the physical theory of rock magnetism, and the magnetic hysteresis loop results used to evaluate the domain structure suggests the amount, size, and other characteristics of the magnetic material. This is critical information necessary in consideration of the temperature and time dependence of magnetic remanence, and the temperature dependence of the induced component of magnetization.

THE INTERPRETATION OF SEISMIC VELOCITIES IN THE CONTINENTAL CRUST BASED ON LABORATORY SEISMOLOGY

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Much of our knowledge of the lower continental crust and upper mantle originates from seismology. Both reflection and refraction studies have provided useful information of crustal structure in many regions throughout the world. Seismic refraction wave velocities also provide additional information on the nature of the continental lithosphere. The interpretation of these velocities in terms of composition relies on laboratory studies of the seismic properties of rocks.

Laboratory investigations of wave velocities in continental rocks are in many ways complicated compared to similar studies of ocean rocks. Deep continental pressures are much higher, so it is often necessary to obtain measurements at confining pressure to 1 GPa. Also, temperature becomes significant in reducing velocities in many lower continental crustal regions and this requires knowledge of temperature derivatives of velocities. Perhaps most important, mapping in high-grade metamorphic provinces has shown that compositional heterogeneity is a characteristic feature of the lower continental crust. In contrast with the oceanic crust, which based on deep sea drilling and studies of ophiolites appears generally basaltic in composition, the lower continental crust probably ranges significantly in composition from region to region.

New measurements of velocities of compressional waves in high-grade metamorphic rocks at hydrostatic confining pressures and temperatures to 500 $^{\circ}C$ show average temperature coefficients $(\partial V_p/\partial T)_p$ of -0.5×10^{-3} km s^{-1} $^{\circ}C^{-1}$ at pressures above 0.5 GPa. Critical thermal gradients $(dT/dz)_c$ for velocity reversals in the lower crust are between 8 and 12 $^{\circ}C$/km. Velocities in continental rocks correlate well with chemical composition. Also of major importance is mineralogy, which is a function of metamorphic grade. Velocity changes associated with progressive metamorphism of pelitic rocks, graywacke, carbonate, basalt, diorite, and granite show complex but well-defined patterns. In general, velocities increase with increasing metamorphic grade; however, for some compositions velocity reversals accompany a progressive isochemical sequence of advancing grade. A similar behavior is observed for shear-wave velocities.

A phenomenon seldom considered in discussions of continental seismic properties but that may be of importance even at lower crustal depths is pore pressure. New measurements in continental rocks at high confining pressures show that both compressional and shear wave velocities are significantly lowered by the application of pore pressure. Within the deep crust, many regional metamorphic reactions involve water. It seems likely that changes in pore pressure accompanying these reactions have significant effects on seismic velocities. Laboratory measurements show high Poisson's ratios may be diagnostic of crustal regions with high pore pressure.

One of the most distinctive features of the fabric of many continental rocks is the tendency for their minerals to assume parallel or partially parallel crystallographic orientation. Preferred orientation of minerals in metamorphic rocks produces appreciable seismic anisotropy for both compressional and shear waves. Distinctive anisotropy patterns characterize different metamorphic mineral assemblages, which is perhaps best illustrated by velocity studies of mylonites from metamorphic core complexes of the southwestern United States. Extreme anisotropy of compressional and shear waves and associated shear-wave splitting are important seismic properties of phyllonites from major thrust zones such as the Brevard of the southern Appalachians. Fabric studies and velocity measurements of ultramafic xenoliths from kimberlites also demonstrate that seismic anisotropy is an important property of the continental upper mantle as well as the continental crust.

GEOLOGICAL AND GEOPHYSICAL NATURE OF THE LOWER CONTINENTAL CRUST AS REVEALED BY EXPOSED CROSS SECTIONS OF THE CONTINENTAL CRUST

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Nearly intact cross sections of the continental crust, exposed in orogenic belts around the world (Fountain and Salisbury, 1981), provide insights into the structure, evolution, and geophysical nature of the lower continental crust. Importantly, these terranes were formed at different times in a variety of tectonic environments, thus providing a spectrum of modes of crustal evolution and structure. Archean cross sections, such as the Pikwitonei and Kapuskasing bodies in the Superior province, represent the deep crust below Archean gneiss-greenstone terranes. The Musgrave and Fraser Ranges in Australia provide glimpses of the deep crust of Proterozoic mobile belts. Several Phanerozoic examples display the lower crust of magmatic arcs (Kohistan in Pakistan, Fiordland in New Zealand, and the Tehachapi Mountains in southern California) and extensional regimes (Ivrea zone, northern Italy). Most of these terranes underwent several tectonic and thermal events during their evolution, thereby providing examples of a variety of deep crustal processes.

The composition of these lower crustal samples is variable with the average chemical composition ranging from tonalitic (for example, Pikwitonei) to mafic (for example, Ivrea, Kapuskasing). Each section is characterized by diverse upper amphibolite-granulite facies lithologies, which may include various proportions of metasedimentary and metavolcanic rocks, layered mafic complexes, anorthosite, tonalite gneiss, mafic gneiss and ultramafic bodies. The presence of isoclinal folds, boudinage structure and, in a few cases, mylonitic shear zones in these terranes attests to the dominance of ductile deformation mechanisms in the lower crust. These structures, coupled with igneous and metamorphic processes, in many cases result in a horizontally layered deep crust from centimeter to kilometer scale.

Efforts are underway to study the physical properties of rocks from these cross sections in order to gain insight into the geophysical nature of the lower continental crust. Laboratory measurements at high confining pressures indicate that there is a wide range in P-wave velocities within any given section. Therefore, large reflection coefficients (>0.15) can be expected. These large reflection coefficients are the result of many factors, including high-grade metamorphic mineral assemblages, intrusion of mafic bodies, and tectonic juxtaposition of diverse rock packages. When coupled with geometrical effects, these reflection coefficients can produce abundant, reflective horizons in the deep crust such as those observed in some COCORP and BIRPS profiles. These effects can be demonstrated on synthetic reflection seismograms.

Large variations in heat production have been measured in rocks from the Pikwitonei, Kapuskasing, and Ivrea lower crustal sections (>0.1 to 1.2 $\mu W/m^3$), and average heat production values (around 0.4 $\mu W/m^3$) are greater than anticipated for the deep crust. These variations may not be resolvable in heat-flow studies because of their relatively small scale. These data indicate that the lower crust may provide a significant contribution to continental heat flow.

Lower crustal rocks have high magnetic susceptibilities, with magnetite constituting the magnetic phase (Williams and others, 1985). Susceptibility is independent of temperature, suggesting that modern lower crust can be a magnetic source in stable regions. Finally, high susceptibility can occur in deep crust rocks of various compositions.

Geophysical interpretations of lower continental crustal structure based on these cross sections must be tempered by considerations of complications introduced by tectonic emplacement of these terranes and the fact that the Moho has not been satisfactorily identified in any of these cross sections. Nevertheless, studies of this type will permit development of realistic geophysical models which can be used to interpret continental geophysical data.

REFERENCES CITED

Fountain, D.M., and Salisbury, M.H., 1981, Exposed cross sections through continental crust: Implications for crustal structure, petrology and evolution: Earth and Planetary Science Letters, v. 56, p. 263-277.

Williams, M.C., Shive, P.N., Fountain, D.M., and Frost, B.R., 1985, Magnetic properties of exposed deep crustal rocks from the Superior Province of Manitoba: Earth and Planetary Science Letters, v. 76, p. 176-184.

THERMAL, SEISMIC, AND PETROLOGIC CHARACTERISTICS OF THE LOWER CRUST AND UPPER MANTLE—A CASE HISTORY BASED ON XENOLITHS FROM EASTERN AUSTRALIA

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Upper mantle and lower crust xenoliths from eastern Australia provide samples of deep-seated rock types whose physical parameters can be used to constrain geophysical modeling. Selected xenoliths can be used for geothermobarometric calculations to determine the temperature and pressure (hence depth) of equilibration of these rocks and to construct a paleogeotherm which represents the ambient geothermal gradient at the time the xenoliths were entrained in the host basaltic magma. Xenoliths in young volcanics (<50 Ma) will reflect the current measurable thermal state of the underlying lithospheric column.

A xenolith-derived geotherm was constructed for present-day southeastern Australia (O'Reilly and Griffin, 1985) using well-equilibrated xenoliths (with ideal assemblages of unzoned garnet+orthopyroxene+clinopyroxene) from two young (<3 Ma) maars in western Victoria. This geotherm gives a much higher temperature at any pressure than conventional continental or even oceanic geotherms. It has a strong curvature from about 1-3 GPa, indicating significant advective transfer of heat in the lower crust and upper mantle, consistent with intrusions of basaltic magmas in those regions. The locus of this geotherm contrasts markedly with that of the steady-state conductive geotherm, which has a shallower curvature at low pressures. This highlights the problems of extrapolating geothermal gradients to depth using surface heat-flow data.

Pressure and temperature data for xenoliths from other Australian basaltic provinces of various ages (200 to 10 Ma) also plot on this geotherm and provide evidence of episodic thermal events over that time span which coincide with volcanism in discrete provinces. The eastern one-third of the Australian continent is relatively young (Paleozoic to Holocene) in contrast with the western two-thirds, which is Precambrian craton. It therefore appears that tectonically active continental regions, especially those with intraplate basaltic activity, are characterized by high geothermal gradients. This contrasts with the lower geothermal gradients of cratons, which correspond more closely with conductive geothermal profiles.

These differences in thermal state of contrasting continental lithosphere types are crucial in the interpretation of seismic data, especially in determining the significance of the attainment of a "mantle" seismic velocity of approximately 8 km/s and higher. The other crucial factor is the real petrological nature of the lower crust and upper mantle.

Using all available xenolith data for eastern Australia (Griffin and O'Reilly, in press; Bezant and others, unpub. data), it is possible to construct a lower crust-upper mantle stratigraphy that is consistent with petrologic, pressure-temperature, and geophysical data. In this model, the crust-mantle boundary lies at about 25 km, which is the depth where ultramafic rocks (spinel lherzolite) become abundant and increase in proportion with depth. Layers of mafic rocks (which range in composition from pyroxenite through gabbro to anorthosite) decrease in proportion away from the crust-mantle boundary (both upward and downward). All lower crustal wallrocks are felsic to mafic granulite.

Reversed seismic profiles for eastern Australia (Finlayson and others, 1979) show that there is a gradient in V_p from about 25 km to 55 km, where V_p is about 8 km/s and thus represents the seismic Moho. This depth of 55 km is the predicted depth where the southeastern Australian geotherm crosses the spinel- to garnet-lherzolite boundary (Griffin and others, 1984). Therefore it is suggested that in continental regions of high geothermal gradient, the seismic Moho may represent the transition from spinel- to garnet-lherzolite, rather than the crust-mantle boundary.

Calculated (O'Reilly and Griffin, 1985) and measured (Bezant and others, unpub. data) V_p's for real mantle rock types are consistent with this interpretation. These V_p values for spinel lherzolites are less than 8 km/s for two main reasons: (1) the higher geothermal gradient lowers V_p and (2) real mantle-derived spinel lherzolite generally contains significant (at least 40 percent) pyroxene, which gives a lower V_p than the olivine-rich rock usually used for modeling the upper mantle.

Xenolith data worldwide (Griffin and O'Reilly, in press) show that the lower crust is dominantly mafic. Therefore different thermal profiles are critical in determining whether or not the equilibrium mineral assemblage lies in the eclogite or the granulite facies, and hence in determining the Vp of these deep-seated regions. As cooling takes place from the high southeastern Australia geotherm to a lower cratonic geotherm, an increasing proportion of mafic rocks converts from granulite to eclogite assemblages, and hence V_p's increase dramatically from about 6.9-7.6 km/s to 7.5-8.5 km/s (Christensen, 1982) for the mafic rocks. The calculated seismic profiles for these differing thermal regimes show that the seismic Moho will roughly coincide with the crust-mantle boundary in cratonic lithosphere. In lithospheric sections with high geothermal gradients, the seismic Moho will lie 20-30 km deeper than the crust-mantle boundary. These calculated V_p-Z profiles closely parallel observed reversed seismic profiles for western and eastern Australia.

With successive cooling, mafic assemblages convert from granulite to eclogite at shallower depths. Because eclogite has significantly higher seismic velocity, the net effect is to decrease successively the depth to the seimic Moho until it coincides with the crust-mantle boundary in stable cratonic areas.

Correlation of the geothermobarometry data with MAGSAT information can lead to mapping of the Curie-point isotherm within the lithosphere and thence to a regional surface heat-flow map. This method of contouring surface heat flow allows interpolation in regions where no direct heat-flow data are available. It also avoids anomalies due to perturbation of surface heat flow measurements by artesian water circulation. In addition, because pressure and temperature are constrained at depth, there is no necessity to assume arbitrarily a steady-state conductive heat-flow model, which may result in misleading extrapolation of heat-flow production to high pressure.

REFERENCES CITED

Christensen, N.I., 1982, Seismic velocities, in Carmichael, R.S., ed., Handbook of physical properties of rocks, v. 2: Boca Raton, Florida, CRC Press, p. 108-133.

Finlayson, D.M., Prodehl, C., and Collins, C.D.N., 1979, Explosion seismic profiles, and implications for crustal evolution in southeastern Australia: BMR Journal of Geology and Geophysics, v. 4, p. 243-252.

Griffin, W.L., and O'Reilly, S.Y., in press, The composition of lower crust and the nature of the continental Moho--Xenolith evidence, in Nixon, P.H., ed., Mantle xenoliths: London, Wiley.

Griffin, W.L., Wass, S.Y., and Hollis, J.D., 1984, Ultramafic xenoliths from Bullenmerri and Gnotuk maars, Victoria, Australia: Petrology of a sub-continental crust-mantle transition: Journal of Petrology, v. 45, p. 53-87.

O'Reilly, S.Y., and Griffin, W.L., 1985, A xenolith-derived geotherm for southeastern Australia and its geophysical implications: Tectonophysics, v. 111, p. 41-63.

CORRELATION OF XENOLITH PETROLOGY AND SEISMIC DATA: AN EXAMPLE FROM EAST-CENTRAL QUEENSLAND

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Some volcanoes in east-central Queensland (148^o-153^o E., 21^o-27^o S.) contain abundant crustal and mantle xenoliths. The surrounding basins are covered by high-quality seismic reflection and refraction data, so this is a good place to relate xenoliths to geophysical models. The volcanism in this region ranges in age from about 55 Ma to <1 Ma; in several provinces an episode of central volcanism, with tholeiite, trachyte and rhyolite occurred in the period 35-25 Ma. The later eruptions are commonly very undersaturated, and include most of the xenolith localities.

Deep seismic reflection studies in the Bowen and Eromanga basins show a "transparent" middle crust and a "layered zone" with numerous sub-horizontal reflectors between 22 and 36-40 km. Refraction data show $V_p \sim 6.0$-6.3 km/s in the transparent zone, with a sharp increase (0.35-0.6 km/s) at the top of the layered zone. V_p increases with the depth through the lower part of this zone, and jumps from ~7.7 to ~8.1 km/s at the bottom of this zone, interpreted as the Moho (Mathur, 1983; Finlayson and others, 1984).

Mantle xenoliths include dominant Cr-diopside spinel lherzolite, minor garnet websterite and Al-augite series pyroxenite. Crustal xenoliths include a variety of two-pyroxene granulite (2px+plag±apat) and garnet granulite (plag+gnt+cpx±opx±qtz). Corona structures show that some of these rocks formed by cooling and recrystallization of gabbroic mineral assemblages. Garnet commonly is broken down to very fine-grained aggregates of 2px+plag+spin; this is interpreted as due to contact metamorphism around crustal magma chambers. Some granulite xenoliths have compositions appropriate to basaltic liquids, but most appear on chemical grounds to be cumulates from basaltic melts.

Pressure and temperature (P-T) calculations for the garnet websterite and garnet granulite are complicated by oxidation of the pyroxenes, breakdown of garnet, and minor zoning of the minerals. Nevertheless, the garnet websterite data fall along the southeastern Australian geotherm of O'Reilly and Griffin (1985), and the garnet granulite data scatter about this line at P = 0.7-1.0 GPa. Temperatures for two-pyroxene granulite are 700-850 ^oC, equivalent to P = 0.6-0.9 GPa, while oliv-opx-sp temperatures on spinel lherzolite are 875-1050 ^oC, equivalent to P = 0.9-1.6 GPa on this geotherm. The data suggest that the southeastern Australia geotherm of O'Reilly and Griffin (1985) is valid for the present area as well. Both areas lie within negative magnetic anomalies on maps of MAGSAT data (Mayhew and Johnson, unpub. data).

The P-T estimates suggest that the granulite xenoliths are derived from depths of approximately 23-30 km, and the lherzolite xenoliths from about 28-55 km. V_p values for the granulite, calculated from density and chemical composition and corrected for T and P, average about 6.7 km/s at 0.8 GPa, and are consistent with measured V_p's in the upper part of the layered zone. Calculated V_p's for the spinel lherzolite are 8.1-8.2 km/s. The V_p gradient from approximately 6.8 to 7.7 km/s with depth in the layered zone suggests a mixture of these two rock types, and the P-T estimates show that spinel lherzolite is the dominant rock type already at 30 km depth. The crust-mantle boundary thus lies within the layered zone, while the seismically defined Moho simply represents the depth where the proportion of relatively low-V_p mafic rocks drops below a critical level.

The layered zone seen on the reflection profiles is therefore interpreted as consisting mainly of mafic granulite in the upper part, and of mixed mafic granulite, pyroxenite, and spinel lherzolite in the lower part. The chemistry and microstructures of the granulite xenoliths, and the apparent contact metamorphism of many of them, suggest that this layered zone formed as the result of repeated intrusions of basaltic melts into the lower crust and uppermost mantle. This conclusion is probably applicable to much of eastern Australia (Griffin and O'Reilly, in press).

REFERENCES CITED

Finlayson, D.M., Collins, C.D.N., and Lock, J., 1984, Wave velocity features of the lithosphere under the Eromanga basin, eastern Australia, including a prominent mid-crustal (Conrad ?) discontinuity: Tectonophysics, v. 101, p. 267-291.

Griffin, W.L., and O'Reilly, S.Y., in press, The lower crust in eastern Australia: Xenolith evidence: Journal of the Geological Society of London.

Mathur, S.P., 1983, Deep reflection experiments in eastern Australia reveal differences in the nature of the crust: First Break, v. 3, p. 9-16.

O'Reilly, S.Y. and Griffin, W.L., 1985, A xenolith-derived geotherm for southeastern Australia and its geophysical implications: Tectonophysics, v. 111, p. 41-63.

CRUST AND UPPER MANTLE BENEATH THE NORTHERN PLAINS: EVIDENCE FROM MONTANA XENOLITHS

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Xenoliths in Eocene intrusions and volcanic rocks in north-central Montana provide data on the chemistry and evolution of a mostly buried terrane of Archean ancestry, and its lower-crustal and upper-mantle roots. This terrane is a northern extension of the Wyoming block of Archean rocks 2.5 Ga and older, which has been overprinted by Proterozoic metamorphism and magma emplacement between 1.7 and 1.9 Ga (Peterman, 1981). Aeromagnetic and gravity patterns indicate discontinuities in the buried Precambrian rocks in eastern Montana (Zietz and others, 1971). Some of these discontinuities have been interpreted as metamorphic and tectonic boundaries, and have had recurrent influence on Phanerozoic sedimentation and shallow tectonic activity.

Seismic studies show crustal thicknesses of 45 to 55 km and present a variety of crustal models. The profile closest to the xenolith sites shows a three-layer model that has an upper layer 3 to 8 km thick with a P-wave velocity of 6.1 km/s, a middle layer 15 km thick with a velocity of 6.4 km/s, a lower layer 25 to 30 km thick with a velocity of 6.6 km/s, and an upper mantle with a velocity of 8.2 km/s (McCamy and Meyer, 1964). In east-central Montana, a north-south profile shows a three-layer model that has a velocity of 6.1 km/s for the depth interval 2 to 20 km, 7.0 km/s for 20 to 35 km, 7.6 km/s for 35 to 55 km, and 8.1 km/s for the upper mantle (McCamy and Meyer, 1964). Intersecting that profile, a profile trending N. 70° E. in the Large Aperture Seismic Array (LASA) shows a two-layer model that has a velocity of 6.1 km/s for the upper crust, 6.7 km/s for the lower crust, and velocity of 8.3 km/s for the upper mantle (Borcherdt and Roller, 1968). More recent studies have found significant lateral variations of velocities beneath LASA that have been interpreted in terms of crustal heterogeneity, or a dipping or offset Moho, or a vertical low-velocity zone extending from the shallow crust to a depth of 140 km in the upper mantle (Glover and Alexander, 1969; Warren and others, 1973; Aki and others, 1976).

The greatest depth range of xenoliths, from the upper mantle to the shallow basement, is found in the Williams kimberlites. The deepest upper-mantle samples are garnet peridotite and megacrysts, which are found in the Williams kimberlites and in the Macdougal Springs diatreme. Spinel peridotite, from the shallow upper mantle, is found in the Williams kimberlites and in three other Missouri Breaks diatremes, and is sparse in a few shonkinite intrusions in the Eagle Buttes, and in the Bearpaw Mountains phonolites. Eclogite is absent from all the xenolith suites.

Xenoliths of probable mid- to lower-crustal origin are mafic to felsic garnet granulite and mafic to felsic garnet amphibolite. Metamorphic textures range from equigranular massive to banded on a scale of 1-3 mm. These are found in the Williams kimberlites, in two other Missouri Breaks diatremes, and in the phonolitic volcanic rocks of the Bearpaw Mountains.

Mid- to shallow-crustal xenoliths of garnet-free amphibolite, pelitic schist and gneiss, gabbro, and granite are found in the above localities and are locally abundant in the Bearpaw Mountains, Eagle Buttes, and Highwood Mountains. Those rock types also make up the exposed Precambrian basement in the core of the Little Rocky and Little Belt Mountains. Biotite-pyroxene-carbonate xenoliths in Missouri Breaks diatremes are enigmatic; these xenoliths are believed to represent carbonate-rich magmas and their cumulates trapped in the lower crust.

Thermobarometry for garnet peridotite xenoliths indicates a perturbed middle Eocene geotherm (Hearn and McGee, 1984). Textures in some xenoliths indicate partial to complete reaction of garnet to a garnet-spinel facies or spinel facies assemblage, with indications of either metasomatic introduction of K_2O or redistribution of K_2O already present in the form of phlogopite and (or) amphibole. Spinel peridotite in Williams kimberlites tends to bear amphibole and (or) phlogopite.

Preliminary chemical data (J.J. Cramer, 1985, written commun.) show a wide compositional range for garnet granulite and garnet amphibolite xenoliths, from nepheline-normative to quartz-normative basalt-like compositions; garnet amphibolite is generally higher in total Fe and more alkaline compared with garnet granulite. Rare-earth patterns also range widely, from primitive (flat REE, 8X chondrite; quartz-normative garnet granulite) to evolved characteristics (LREE-enriched, La 80-140X chondrite, Lu 7-15X chondrite; nepheline-normative garnet amphibolite), and suggest that the lower crust here has had a complex evolutionary history.

Xenolith lithologies can be correlated tentatively with the two-layer and three-layer seismic-velocity models. The upper crust (6.0-6.1 km/s) probably consists of felsic pelitic schist and gneiss, gabbroic and granitic intrusions, and felsic amphibolite. In the two-layer model, the lower crust (6.7 km/s) could consist of garnet amphibolite and garnet granulite, with interlayered felsic, intermediate, and mafic types (based on composite xenoliths). In the three-layer models, the middle crust (6.4 or 7.0 km/s) could consist of felsic and intermediate garnet amphibolite and garnet granulite, and the lower crust (6.6 or 7.6 km/s) could consist of mainly mafic garnet-pyroxene-rich granulite. Other lithologic distributions are possible, such as garnet amphibolite being dominant in the middle crust, and garnet granulite being dominant in the lower crust.

However, the densities of probable lower crustal xenoliths do not fit the lower crustal seismic velocity in the nearest profile. The measured densities for 14 felsic to mafic granulite and amphibolite xenoliths range from 2.67 to 3.44 g/cm^3, and average 3.01 g/cm^3. For a depth of 30 km, based on the data of Christensen and Fountain (1975), these densities imply P-wave velocities ranging from 6.5 to 8.0 km/s and averaging 7.3 km/s, much higher than the 6.6 km/s velocity for the lowermost crust in the nearest seismic profile. Possible explanations are that (1) the xenolith suite is biased by the diatremes or by the collector, or (2) the seismic profile is not representative of the crust beneath the diatremes because of limited resolution of the seismic experiment or lateral heterogeneities in the lower crust. The xenolith data suggest that a lower crustal layer having a velocity that averages 7.0 to 7.6 km/s actually is present. Further seismic modeling and research on geochemical and geophysical properties should provide greater resolution.

REFERENCES CITED

Aki, K., Christoffersson, A., and Husebye, E.S., 1976, Three-dimensional seismic structure of the lithosphere under Montana LASA: Seismological Society of America Bulletin, v. 66, no. 2, p. 501-524.

Borcherdt, C.A., and Roller, J.C., 1968, Preliminary interpretation of a seismic refraction profile across the large aperture seismic array, Montana: U.S. Geological Survey Open-File Report, 31 p.

Christensen, N.I., and Fountain, D.M., 1975, Constitution of the lower continental crust based on experimental studies of seismic velocities in granulite: Geological Society of America Bulletin, v. 86, no. 2, p. 227-236.

Glover, P., and Alexander, S.S., 1969, Lateral variations in crustal structure beneath the Montana LASA: Journal of Geophysical Research, v. 74, no. 2, p. 505-531.

Hearn, B.C., Jr., and McGee, E.S., 1984, Garnet peridotites from Williams kimberlites, north-central Montana, U.S.A., in Kornprobst, J., ed., Kimberlites II: The mantle and crust-mantle relationships: Amsterdam, Elsevier, p. 57-70.

McCamy, K., and Meyer, R.P., 1964, A correlation method of apparent velocity measurement: Journal of Geophysical Research, v. 69, no. 4, p. 691-699.

Peterman, Z.E., 1981, Archaean gneisses in the Little Rocky Mountains, Montana: U.S. Geological Survey Professional Paper 1199-A, p. A1-A6.

Warren, D.H., Healy, J.H., Bohn, J., and Marshall, P.A., 1973, Crustal structure under LASA from seismic refraction measurements: Journal of Geophysical Research, v. 78, no. 35, p. 8721-8734.

Zietz, I., Hearn, B.C., Jr., Higgins, M.W., Robinson, G.D., and Swanson, D.A., 1971, Interpretation of an aeromagnetic strip across the northwestern United States: Geological Society of America Bulletin, v. 82, no. 12, p. 3347-3372.

THE MANTLE BENEATH THE RED SEA RIFT: XENOLITHS FROM WESTERN SAUDI ARABIA

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Formation of the Red Sea was accompanied by eruption of large volumes of alkaline basalt on the Red Sea margin of the Arabian continental shield. At least nine Saudi Arabian basalt fields contain xenoliths of mantle and crustal material. The mantle nodules provide a unique opportunity to study the mantle beneath the Saudi Arabian Red Sea margin.

Two Saudi Arabian mantle xenolith localities have been described previously: Al Birk, by Ghent and others (1980), and Harrat Hutaymah, by Thornber and Pallister (1985). This study examines the mantle xenolith suite from Harrat al Kishb in western Saudi Arabia. Harrat al Kishb is a large (6,700 km^2) volcanic plateau of Pliocene-Pleistocene to Holocene age. The alkaline olivine basalts of Harrat al Kishb contain abundant xenoliths of mantle and crustal rocks that have been collected by R.G. Coleman during his work with the U.S. Geological Survey in Saudi Arabia. The al Kishb mantle suite consists of a variety of Type I and Type II spinel-bearing peridotite and pyroxenite nodules, several garnet-spinel-amphibole-bearing pyroxenites, and one lherzolite transitional between Types I and II. Several rare composite nodules show relations between some of these mantle lithologies.

The al Kishb Type I nodules exhibit far greater variation in lithology, mineral composition, and textures than Type II. Type I nodules are dominantly coarse-grained allotriomorphic-granular harzburgite and lherzolite. Pyroxenes have exsolved spinel and many are zoned, apparently due to re-equilibration to lower temperature conditions. Type I nodules are Mg-Cr rich, containing Cr-diopside, olivine with $Fo_{90-91.5}$, and Mg-Cr rich spinel. Type I websterite crystallized at high temperature as subcalcic diopside and has exsolved and recrystallized with cooling. One composite nodule contains a 6-cm-wide vein of Type I websterite within Type I peridotite.

Al Kishb Type II xenoliths are dominantly websterite and clinopyroxenite. Textures range from mosaic-equigranular to porphyroclastic, to allotriomorphic-granular with consertal grain boundaries suggestive of an igneous origin. Type II nodules are rich in Al, Fe, and Ti, and poor in Mg and Cr, relative to Type I xenoliths. One composite nodule contains a 5-6-cm-wide vein of Type II pyroxenite within Type I peridotite. Type II pyroxenite apparently formed by crystallization of aluminous augite and spinel from basaltic liquids within veins in the mantle. Subsequent exsolution and recrystallization occurred in response to decreasing temperature.

Intrusion of basaltic veins into the mantle may alter the peridotite surrounding the veins. One nodule of transitional lherzolite from Harrat al Kishb may represent peridotite from a reaction zone bordering a vein. The nodule mineral chemistry is transitional between Type I and II, and is compositionally zoned across the xenolith. One edge of the nodule is enriched in Fe and Al, and depleted in Mg and Cr. As one traverses the nodule, away from this one edge, Fe and Al decrease steadily and Mg and Cr increase. Apparently the xenolith edge was at or near a contact with a vein.

Several unusual garnet-spinel-amphibole-bearing pyroxenite xenoliths have been found at Harrat al Kishb. These nodules contain anhedral garnet forming "coronas" around rounded anhedral spinel. Ti-rich pargasite is always present in these nodules, and is not found in any garnet-free nodules from al Kishb. The compositions of pyroxene and spinel from these nodules are similar to other Type II spinel pyroxenites, except that the garnet-bearing pyroxenites are more Fe, Ti, and Na rich.

In summary, the variety of lithologies, compositions, and textures within the Harrat al Kishb mantle xenolith suite is indicative of a heterogeneous upper mantle beneath western Saudi Arabia. The estimated range of temperatures and pressures of reequilibration of Harrat al Kishb mantle xenoliths is about 900-1150 ^{o}C, at about 1.5-2.2 GPa. Compared to a stable continental geotherm, this pressure-temperature range suggests elevated temperatures in the mantle, presumably due to mantle upwelling beneath the Red Sea rift. Exsolution and recrystallization textures of al Kishb mantle nodules suggest reequilibration to decreasing temperatures, and possibly pressure, within the upwelling mantle beneath the Saudi Arabian Red Sea margin.

REFERENCES CITED

Ghent, E.D., Coleman, R.G., and Hadley, D.G., 1980, Ultramafic inclusions and host alkali olivine basalts of the southern coastal plain of the Red Sea, Saudi Arabia: American Journal of Science, v. 280-A, p. 499-527.

Thornber, C.R., and Pallister, J.S., 1985, Mantle xenoliths from Northern Saudi Arabia [abs.]: Eos, Transactions, American Geophysical Union, v. 66, p. 393.

A MECHANISM FOR THE INCORPORATION OF UPPER MANTLE MATERIAL INTO THE MIDDLE AND UPPER CRUST: EVIDENCE FROM SOUTHERN ALASKA

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Ideas regarding the possible composition of the lower crust are necessarily limited by what we view as "reasonable" given known geologic processes. Recent seismic refraction measurements in southern Alaska provide evidence for the incorporation of large amounts of mafic and ultramafic oceanic rocks into the continental crust. Underplating of the continent by paleosubduction zone complexes is the mechanism responsible.

Southern Alaska is an area that is generally agreed to consist of a mosaic of oceanic and continental fragments that have been accreted to the continental margin of North America in the past 200 m.y. Paleomagnetic studies indicate that these terranes have moved north thousands of kilometers relative to the North American craton since the early Mesozoic. The seismic refraction profiles described here provide the first information on the deep crustal structure of the various terranes.

Seven hundred kilometers of seismic refraction profiles were recorded in southern Alaska in 1984 and 1985. The profiles were shot as part of the Trans-Alaska Crustal Transect (TACT) program--a combined geological and geophysical study of the structure, composition, and evolution of the Alaskan crust from the Pacific Ocean to the Arctic continental margin.

Our interpretation of the seismic refraction data is that the accretionary Chugach terrane and the composite Peninsular/Wrangellia terrane are underlain by an extensive sequence of continuous, north-dipping alternating low- and high-velocity layers. Velocities within the high-velocity layers are appropriate for ultramafic rocks. Each layer could in fact be considered "Moho." We interpret these layers as a stack of oceanic plates that have been subducted, the deepest plate being the youngest and currently subducting plate, while the upper plates have already been incorporated into the continental crust. This interpretation implies that continental growth in southern Alaska is in part accomplished by the underplating of paleosubduction zones at the active continental margin. On the basis of similar results obtained on Vancouver Island to the south, we believe that underplating may be a generally important mechanism for the incorporation of mafic and ultramafic rocks into the continental crust.

THE LOWER CRUST AND UPPER MANTLE BENEATH THE SIERRA NEVADA BATHOLITH: EVIDENCE FROM XENOLITHS IN LATE CENOZOIC VOLCANIC ROCKS

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Xenoliths from several small late Cenozoic volcanic plugs, pipes, and flow remnants provide a sampling of the lower crust and upper mantle underlying the central Sierra Nevada batholith. The nature of the xenoliths varies, apparently systematically inward from the margins to the core of the batholith.

Localities of xenolith-bearing rocks at the edges of the batholith include the Jackson Butte and Golden Gate Hill dacite domes on the west side and the Oak Creek and Waucoba basalt flows on the east side. Fragments of near-surface country rock are the most common xenolith type, although magnesian peridotite xenoliths, generally of hornblende- or spinel-bearing lherzolite, are also present at these sites. The magnesian peridotite (Cr-diopside ultramafic group of Wilshire and others, 1985) is representative of mantle materials under the batholith's margins.

Contrasting xenolith suites occur at three major and several associated minor localities concentrated in the core of the batholith. Peridotite and olivine-bearing pyroxenite as well as partially fused gabbroid and granitoid are common inclusions in the Blue Knob alkali basalt plug. A variety of high-grade metamorphic, commonly garnet-bearing xenoliths, including abundant eclogite and granulite, and batholithic rock fragments, are present in an andesite pipe near the town of Big Creek. Olivine-free pyroxenite dominates the xenolith assemblage, that also contains abundant plagioclase-rich granulite and sparse Fe-rich peridotite in a trachybasalt flow remnant capping Chinese Peak.

These suites are believed to represent different source levels beneath the batholith. Blue Knob ultramafic xenoliths may have been derived from upper mantle materials. Ultrapotassic basalt related to the Blue Knob intrusion was generated at pressures greater than 2.0 GPa (Van Kooten, 1980; Dodge and Moore, 1981). The garnet-bearing Big Creek inclusions were largely derived from ancient mafic oceanic floor materials; preliminary geobarometric estimates indicate equilibration at pressures of 1.5 to 1.7 GPa. Chinese Peak xenoliths represent a continental mafic-ultramafic complex intruded into a granulite terrane. Crystallization pressure of approximately 1.5 GPa has been determined on Chinese Peak xenoliths.

Coupling of the xenolith and other surface data with a seismic-density profile across the central Sierra Nevada (Oliver, 1977) permits construction of a meaningful model of the crust and mantle beneath the batholith. The felsic granitoid and associated greenschist- to amphibolite-grade metamorphic rocks of the batholith make up a surface seismic-density layer (V_p = 6.0 km/s, ρ = 2.67) that extends only to a depth of 10 to 15 km. Studies in the southermost Sierra Nevada, where deeper crustal levels are exposed (Ross, 1985), indicate that a largely meta-igneous assemblage of hornblende-rich gneissic amphibolite- to granulite-grade rocks underlies the batholith and indeed may form its roots. These rocks form a roughly 10 km thick lens of the upper crust that thins toward the margins of the batholith. The lower portion of the crust (V_p = 6.9 km/s, ρ = 3.03) constitutes about half the entire crust. Its upper part is made up of a series of deformed mafic-ultramafic intrusions that cut granulite-grade metasedimentary rocks. Mafic eclogite occurs at greater depths and may, perhaps with the disappearance of a minor phase, such as hornblende, span the crust-mantle seismic boundary. Olivine-rich ultramafic igneous rocks occur exclusively at greater mantle depths and in the mantle beneath the margins of the batholith.

REFERENCES CITED

Dodge, F.C.W., and Moore, J.G., 1981, Late Cenozoic volcanic rocks of the southern Sierra Nevada, California: II. Geochemistry: Geological Society of America Bulletin, Part I, v. 92, p. 912-914.

Oliver, H.W., 1977, Gravity and magnetic investigations of the Sierra Nevada batholith, California: Geological Society of America Bulletin, v. 88, p. 445-461.

Ross, D.C., 1985, Mafic gneissic complex (batholithic root?) in the southernmost Sierra Nevada, California: Geology, v. 13, p. 288-291.

Van Kooten, G.K., 1980, Mineralogy, petrology, and geochemistry of an ultrapotassic basaltic suite, central Sierra Nevada, California, U.S.A.: Journal of Petrology, v. 21, p. 631-684.

Wilshire, H.G., and others, 1985, Mafic and ultramafic xenoliths from volcanic rocks of the western United States: U.S. Geological Survey Open-File Report 85-139, 49 p.

THE GROUND TRUTH FROM CRUSTAL XENOLITHS: A MULTIFACETED APPROACH

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Direct sampling of rock types that characterize the Earth's lithosphere is limited to outcrops, drill cores, and fragments (xenoliths) brought to the Earth's surface by erupting magmas. Xenoliths can provide important information about crustal evolution at depth and can place constraints on properties of the lower crust and crust-mantle interface from geophysical measurements. Such calibration is critical for refining models of rheological structure and transport phenomena in the continental lithosphere. Because xenolith suites are nonrenewable, a multifaceted analytical approach should be undertaken wherever samples of sufficient size and abundance are encountered, and after establishing that in situ properties have not been overprinted by the emplacement process.

Projects that have integrated petrology and geochemistry of xenolith suites with geophysical studies are few. In the United States, two xenolith occurrences have received intensive scrutiny from both geophysical and petrological perspectives. Studies of samples from Kilbourne Hole and Potrillo maars in the southern Rio Grande rift, and from Moses Rock dike and the Mule Ear diatreme on the Colorado Plateau, are good examples of what can be done to improve our understanding of the chemical and physical properties of crustal depths below our present drilling capabilities (see McGetchin and Silver, 1972; Padovani and Carter, 1977; Hart and others, 1979; Padovani and Hart, 1981; Wasilewski and Padovani, 1981; Padovani and others, 1982; Reid and others, 1985; Wandless and Padovani, 1985). At the same time, these studies reveal pitfalls that must be avoided if xenolith suites are to be utilized to their fullest potential. The following brief discussion touches on models of the crust and upper mantle, and on techniques used to ensure the best possible use of material available for both geophysical and geochemical purposes.

RIO GRANDE RIFT

Techniques.--The crustal xenolith suites at Kilbourne Hole and Potrillo maars are exceptional because of the variety and abundance of rock types sampled from middle to lower crustal depths. In addition, their large size (10-40 cm maximum diameter) has permitted a spectrum of observations and analyses to be made on individual samples. Preliminary petrographic and electron microprobe analyses revealed that most samples are pristine, and, except for minor amounts of decompression melting, have anisotropies and mineralogies that are representative of in situ conditions at depth. Techniques used to maximize information from each sample were: (1) photographic documentation before and after sawing, coring, and numbering; (2) acquisition of oriented cores where possible for geophysical measurements; (3) preservation of a reference slab for archival purposes; 4) preparation of sufficient material from an adjacent representative slab to accommodate the requirements of a variety of geochemical analyses; and (5) preparation of a sufficient number of polished thin sections to allow complete characterization of major- and minor-element geochemistry of mineral phases across the slab used for other types of geochemical analysis. Approximately 20-25 xenoliths have been characterized with respect to mineralogy, seismic velocity, density, magnetic properties, major-, minor-, and trace-element compositions, and (or), isotopic signatures (Rb/Sr, Sm/Nd, U/Th/Pb, O).

Pitfalls.--Major pitfalls to be avoided in studying this type of xenolith suite are associated with sample preparation and with nonrecognition of decompression melt and (or) its melt crystallization products, all of which can lead to gross misinterpretations of physical properties and petrogenesis.

Model.--The lower crust beneath the southern Rio Grande rift is dominated by metasedimentary and meta-igneous granulites and appears to be of intermediate composition. Rb/Sr and 207/204-206/204 Pb isochrons give apparent ages of 1.6-1.7 Ga for the crust in this region, but both Rb/Sr and Sm/Nd mineral isochrons within the xenolith suite give ages of 0-37 Ma. Oxygen isotopic compositions are typical crustal values and do not have a recognizable mantle component. These data suggest that the lower crust cooled to a stable shield geothermal gradient after cratonization and then was reheated to 750-900 ^{o}C during magmatic activity related to opening of the Rio Grande rift until the crust was sampled by maar eruptions 0.125 m.y. ago.

Laboratory measurements yield intermediate velocities for lower crustal xenoliths of felsic granulite, which have densities of 2.9-3.1 g/cm^3. Ilmenite-dominated mineralogies and elevated temperatures in the lower crust are responsible for the shallow Curie isotherm at 10-15 km, thus regional magnetic anomalies are due to both the topology of the Curie isotherm and petrologic variations within the crust. These results agree with observed properties of the lower crust from geophysical measurements (Jiracek and others, 1979; Seager and Morgan, 1979; Baldridge and others, 1984) and suggest that crustal granulite may have a major influence on observed properties of the crust in reactivated intracontinental rifts.

COLORADO PLATEAU

Techniques.--Crustal xenolith suites from Moses Rock dike and Mule Ear diatreme were sampled in order to compare observed seismic velocity structure beneath the Colorado Plateau with velocities measured on representative xenoliths. In contrast to the rift samples, most Colorado Plateau xenoliths have suffered extensive hydrothermal alteration during and (or) after emplacement, an effect not recognized by McGetchin and Silver (1972). However, systematic collection from the dikes resulted in specimens that exhibit a spectrum of alteration in the same rock type from "pristine" to "altered." Due to the small size of the "pristine" samples (8-15 cm maximum diameter), drilling of cores was given highest priority, and unused portions of cores and remnents were reserved for electron microprobe, scanning electron microscope (SEM) and petrographic analyses.

Pitfalls.--The major pitfall in the study of this type of xenolith suite is nonrecognition of hydrothermal overprinting of lower crustal amphibolite and granulite. Petrography and SEM observations reveal a direct correlation between progressive alteration and presence of microcracks extending into the xenoliths from the kimberlitic host. In addition, seismic velocities measured in altered samples are too low for such rocks to be characteristic of deep crustal levels.

Model.--Seismic velocities measured on or calculated for pristine samples agree with crustal velocity models, but not with the crustal model of McGetchin and Silver (1972). It is concluded that the crust below 15 km is not hydrated on a major scale and that the "greenschist facies event" postulated for the lower crust by these authors is more likely "localized" in each xenolith as a result of the emplacement process. The crustal reconstruction of Padovani and others (1982) results in a profile that has similarities to the Ivrea Zone (Fountain, 1976) and is characterized by rhyolite, granite, and low-grade metamorphic rocks in the upper crust, and by mafic, garnet-bearing amphibolite and intermediate to mafic granulites in the lower crust.

SUMMARY

To achieve the most benefit from available xenolith material, it is clear that a multifaceted approach is needed. The examples cited reflect some of the information to be gained and pitfalls to be encountered in the study of xenolith suites from contrasting crustal environments. A coordinated approach from the petrologic, geochemistry, and geophysical communities is clearly needed if we are to profit from the potential knowledge to be gained fron the xenolith suites.

REFERENCES CITED

Baldridge, W.S., Olsen, K.H., and Callender, J.F., 1984, Rio Grande rift: Problems and perspectives, in Guidebook, 35th Field Conference, Rio Grande Rift: Northern New Mexico: Santa Fe, New Mexico Geological Society, p. 1-12.

Fountain, D.M., 1976, The Ivrea-Verbano and Strona-Ceneri zones, northern Italy: A cross-section of the continental crust--New evidence from seismic velocities of rock samples: Tectonophysics, v. 33, p. 313-327.

Hart, S.R., Padovani, E.R., and Roden, M.K., 1979, Sr-isotopic relationships in lower crustal nodules from Kilbourne Hole, New Mexico [abs.]: Geological Society of America Abstracts with Programs, v. 7, no. 7, p. 439.

Jiracek, G.R., Ander, M.E., and Holcombe, H.T., 1979, Magnetotelluric soundings of crustal conductive zones in major continental rifts, in Riecker, R.E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 208-222.

McGetchin, R.R., and Silver, L.T., 1972, A crustal-upper-mantle model for the Colorado Plateau based on observations of crystalline rock fragments in Moses Rock Dike: Journal of Geophysical Research, v. 77, p. 7022-7037.

Padovani, E.R., and Carter, J.L., 1977, Aspects of deep crustal evolution beneath south central New Mexico, in Heacock, J.G., ed., The Earth's crust, its nature and physical properties: Washington, D.C., American Geophysical Union, p. 19-55.

Padovani, E.R., Hall, J., and Simmons, G., 1982, Constraints on crustal hydration below the Colorado Plateau from V_p measurements on crustal xenoliths: Tectonophysics, v. 84, p. 313-328.

Padovani, E.R., and Hart, S.R., 1981, Geochemical constraints on the evolution of the lower crust beneath the Rio Grande Rift, in Conference on the processes of planetary rifting: Napa, California, Lunar Planetary Institute Contribution No. 457, p. 149-152.

Reid, M., Hart, S.R., and Padovani, E.R., 1985, Importance of sedimentary protoliths to the lower crust exemplified by Kilbourne Hole paragneisses - Sr, Nd, Pb, isotope geochemistry: Eos, Transactions, American Geophysical Union, v. 66, no. 46, p. 1110.

Seager, W.R., and Morgan, P., 1979, Rio Grande Rift in southern New Mexico, west Texas, and northern Chihuahua, in Reicker, R.E., ed., Rio Grande Rift: Tectonics and Magmatism: Washington, D.C., American Geophysical Union, p. 87-106.

Wandless, G.A., and Padovani, E.R., 1985, Trace element geochemistry of lower crustal xenoliths from Kilbourne Hole maar, New Mexico: Eos, Transactions, American Geophysical Union, v. 66, no. 46, p. 1110.

Wasilewski, P.J., and Padovani, E.R., 1981, Crustal magnetization beneath the Rio Grande rift based on xenoliths from Kilbourne Hole and Potrillo maar: Conference on the processes of planetary rifting, Napa, Calif., Lunar Planetary Institute Contribution no. 457, p. 153-155.

NEW VIEW OF THE CONTINENTAL CRUST FROM SEISMIC REFLECTION PROFILING

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Below the sedimentary section, the crystalline crust of the continents has long been defined by seismic refraction P-wave velocities of about 5-7 km/s and the mantle below by velocities greater than about 7.8 km/s. The transition so defined is the M discontinuity. The observed crustal velocities are appropriate for silicic to mafic igneous and metamorphic rocks, such as those exposed in deeply eroded mountain belts, including granulite and serpentinized ulramafic rocks. The upper mantle velocities are appropriate for peridotite and eclogite. Multichannel seismic reflection profiling has increased the resolving power in the deep crust from kilometers to about 100 m and revealed that the crust in many regions is full of reflectors in contrast to a comparatively transparent mantle. Thus the "reflection Moho" is generally picked as the base of the reflective section; it is usually marked also by a zone of discontinuous higher amplitude reflectors; this zone in the basal part of the crust is one-half to several kilometers thick.

Perhaps the most surprising revelation of the reflection sections is the subhorizontal layered fabric seen in large parts of the crystalline crust. Deep-seated zones of thrust and normal faulting (mylonites) are also well imaged, and these inclined reflectors add assurance that the subhorizontal relectors are not an artifact of the method.

A representative reflection section in a tectonically active region with granitic plutons at the surface might consist, from the top down, of (1) a nearly transparent section (few reflectors) to a depth of 10 km or so, (2) several kilometers of discontinuous subhorizontal reflectors that suggest high and low velocities, (3) a few kilometers of fewer reflectors or nearly transparent section, and (4) a kilometer or more of subhorizontal reflectors at the base of the crust. The available interpretations for (2) range from igneous through metamorphic to tectonic. An igneous interpretation may suggest tabular mafic intrusions underplating the granitic terrane; the mafic intrusions might be interlayered with gneiss and might contain cumulate layers. A tectonic interpretation necessarily emphasizes subhorizontal zones of ductile deformation below the brittle, seismogenic upper crust; contrasting lithologies sheared out horizontally into a roughly layered mass would fit the reflection data. Micaceous minerals have a much lower velocity perpendicular than parallel to their cleavage and can strongly influence the reflectivity of layered mylonites.

The interpretation of the lowest, Moho reflectors must also consider tectonic and igneous possiblities. In active regions such as the Basin and Range, the Moho seems to cut and be superimposed upon all the older structures. It may be a zone of shear and flow in the thermally softened rocks just above the stronger mantle peridotite. The laminated appearance, however, requires interlayering of contrasting rocks on a scale of tens to hundreds of meters; the Ivrea zone is one possible model. A combination of partial melting and metamorphism of lower crust, mafic intrusions from the mantle, and concentrated deformation within the soft zone near the base of the crust seems likely.

EVIDENCE FOR MOHO EVOLUTION IN OROGENIC BELTS BASED ON COCORP PROFILES

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COCORP deep seismic reflection profiling along four transects of Phanerozoic orogens in the United States (two Appalachian transects and two Cordilleran transects) has shown that high-amplitude, relatively flat and continuous Moho reflections occur beneath orogenic interiors (characterized by thick-skinned thrusting and post-thrusting crustal extension), while the reflection Moho becomes much less distinct as seismic profiles cross from orogenic interiors into thin-skinned thrust belts. Examples of these transitions occur in the eastern Great Basin (Allmendinger and others, in press), eastern Washington-northwestern Montana (Potter and others, in press), the Georgia Piedmont (Cook and others, 1981; Nelson and others, 1985), and the New England Appalachians (Ando and others, 1984). Beneath thin-skinned thrust belts and cratonic areas, the reflection signature of the Moho is a downward disappearance of reflections, rather than a prominent set of reflections. The following characteristics suggest that, in regions where overthickened crust developed during compressional orogenesis, the position and geometry of the Moho have evolved after thrusting: (1) the occurrence of Moho reflections as very prominent, relatively flat features confined to orogenic interiors, (2) the fairly constant 30-35 km depth to Moho in these regions, and (3) angular relationships preserved (and observed on seismic profiles) between the reflection Moho and dipping lower crustal structure.

Cordilleran examples of the well-defined "reflection Moho" occur under the Basin and Range in Nevada along a COCORP traverse at about 40 ^{o}N latitude (Klemperer and others, 1987), the crystalline complexes of northeastern Washington and northern Idaho (Potter and others, in press), as well as Death Valley and the Mojave Desert (Cheadle and others, 1986). In the Appalachians, apparently similar Moho reflections occur beneath the Georgia coastal plain and in New Hampshire. In the Appalachian examples the subhorizontal Moho reflections underlie dipping crustal reflections that are interpreted as Paleozoic thrusts (Ando and others, 1983; Nelson and others, 1985). In all of these places, the Moho reflections are at two-way travel times of 10-11.5 s (about 30-35 km).

The Moho varies smoothly and continuously beneath a complexly deformed crust in these interior regions, and there are several examples of angular relationships between dipping deep crustal structures and the relatively flat Moho. Beneath central Georgia, dipping reflections which mark the Alleghenian suture can be traced nearly to the Moho; preliminary migration studies indicate that the deepest of the dipping suture-related reflections in the lower crust are truncated by a horizontally laminated reflection sequence at two-way travel times appropriate for the Moho (Nelson and others, 1985). In the Cordilleran interior of the northwestern United States, gently east-dipping reflections, interpreted as broad ductile deformation zones related to Eocene extension, appear to sole into the

Moho; west-dipping reflections from thrust structures can also be traced into the deep crust (Potter and others, in press). Beneath eastern Nevada, a crust-penetrating normal fault can be traced to, but not deeper than, the Moho (Hauser and others, in press). These examples strongly suggest that the geometry and position of the Moho evolves dynamically beneath orogenic belts, with significant Moho adjustments occurring after major episodes of crustal shortening. The well-defined reflection Moho appears confined to regions where post-thrusting magmatism and extension was important; thus, its development may be related to magmatic processes in the lowermost crust (both underplating from mantle-derived magmas and partial melting of the deep crust). In addition, examples listed above suggest that high strain zones along the Moho may have accommodated large displacements during post-thrusting extension.

REFERENCES CITED

Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J., and Oliver, J.E., in press, Tectonic heredity and the layered lower crust in the Basin and Range Province, western United States: Geological Society of London Special Volume on Extensional Tectonics.

Ando, C.J., Czuchra, B.L., Klemperer, S.L., Brown, L.D., Cheadle, M.J., Cook, F.A., Oliver, J.E., Kaufman, S., Walsh, T., Thompson, J.B., Lyons, J.B., and Rosefeld, J.L., 1984, Crustal profile of mountain belt: COCORP deep seismic reflection profiling in New England Appalachians and implications for architecture of convergent mountain chains: American Association of Petroleum Geologists Bulletin, v. 68, p. 819-837.

Cheadle, M.J., Czuchra, B.L., Ando, C.J., Byrne, T., Brown, L.D., Oliver, J.E. and Kaufman, S., in press, Geometries of deep crustal faults: Evidence from the COCORP Mojave survey, in Barazangi, M., and Brown, L.D., eds., Reflection seismology: The continental crust: Washington, D.C., American Geophysical Union, Geodynamics Series, v. 14.

Cook, F.A., Brown, L.D., Kaufman, S., Oliver, J.E., and Petersen, T.A., 1981, COCORP seismic profiling of the Appalachian orogen beneath the coastal plain of Georgia: Geological Society of America Bulletin, Pt. 1, v. 92, p. 738-748.

Hauser, E.C., Burgess, S., Burtch, S., Mutschler, J., Potter, C.J., Hauge, T.A., Allmendinger, R.W., Brown, L.D., Kaufman, S., and Oliver, J.E., in press, Crustal structure of eastern Nevada from COCORP deep seismic-reflection data: Geological Society of America Bulletin.

Klemperer, S.L., Hauge, T.A., Hauser, E.C., Oliver, J.E., and Potter, C.J., 1986, The Moho in the northern Basin and Range, Nevada, along the COCORP 40 °N. seismic-reflection transect: Geological Society of America Bulletin, v. 97, p. 603-618.

Nelson, K.D., Arnow, J.A., McBride, J.H., Willemin, J.H., Huang, J., Zheng, L., Oliver, J.E., Brown, L.D., and Kaufman, S., 1985, New COCORP profiling in the southeastern United States, Part 1: Late Paleozoic suture and Mesozoic rift basin: Geology, v. 13, p. 714-717.

Potter, C.J., Sanford, W., Yoos, T., Prussen, E., Keach, R.W., Oliver, J.E., Kaufman, S., and Brown, L.D., in press, Deep seismic profiles across the interior of the north American Cordillera, Washington and Idaho: Implications for orogenic evolution: Tectonics.

CONSTRAINTS ON THE PHYSICAL NATURE OF DEEP CRUSTAL STRUCTURES IN SOUTHEASTERN CALIFORNIA FROM THE CALCRUST SEISMIC REFLECTION EXPERIMENT

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Seismic reflection studies of deep-crustal structures have, to this date, concentrated on imaging the geometry of the reflectors. While reflector geometry can be useful in the geologic interpretation of these structures, many ambiguities regarding the physical nature of deep reflectors remain. Reflections from deep crustal structures beneath the Mojave Desert of California were first recognized by Dix in 1965. The multiplicity and strength of the reflections he recorded led him to believe that the velocity of the crust could oscillate with depth, rather than increase monotonically. The more extensive COCORP survey across the western Mojave succeeded in imaging the geometry of several deep-crustal reflectors over a wide area (Cheadle and others, 1986). With the exception of one reflection which they believe can be traced to surface exposures, Cheadle and others' (1986) geologic interpretation of the mid- and deep-crustal reflections was guided by the geometry in stacked sections. They consider the major reflectors to be detachment fault structures. This interpretation ignores the possibility, proposed by Kosminskaya (1964), that crustal velocity discontinuities may be due to the effect of physical conditions such as pressure or temperature. It is this possibility that motivated the CALCRUST consortium to add a secondary experiment to record reflections from the deep crust during its May-June 1985 seismic reflection survey in the eastern Mojave Desert.

Both of the previous surveys had used only the arrival time and "character" of the recorded reflections in their interpretations. The character of the reflections they evaluated was the average character over the entire source-to-receiver offset range of the experiment such as on a stacked seismic section. However, much more information is available in the multioffset seismograms which can be used to constrain the physical properties of the reflector, such as changes in compressional and shear velocity and density. We separate the problem of inverting the seismograms for such properties into two parts. The first-order problem is determining whether the reflector constitutes an abrupt change in these properties (a step discontinuity), is a more gradual variation over some depth range (a gradient), or is composed of layers having thicknesses on the same scale as the seismic wavelength (the simplest case of which is an isolated thin layer). The ability to classify observed reflections into one of these three categories is crucial for deciding whether the structures represent major changes in composition or physical conditions, or are the result of fault movement. The second-order problem is to use the variation of reflection amplitude with offset to yield information on the relative changes in the velocities and density. Such information is needed to decide whether the structures represent changes in mineralogy or are due to variations in physical properties such as porosity or anisotropy.

The aim of our initial effort is to distinguish whether step discontinuity, gradient, or thin-layer models best fit the character of the deep-crustal reflections observed by the CALCRUST survey. We investigated the reflection spectral response of the three conceptual models through elastic finite-difference modeling in two dimensions. The synthetics show that a thin layer produces a distinctive increase in the peak frequency of the reflection with offset. This increase is adequately described by simple acoustic interference relations which allow the thickness and velocity of the thin layer to be derived from the dispersion.

The spectra of normal-incidence reflections were used to support the concept of a layered Moho and derive layer thicknesses on the order of 100 m (Clowes and Kanasewich, 1970; Meissner, 1973). Later workers (Hale and Thompson, 1982; Jones and Nur, 1984; Jones, 1985) combined these ideas with laboratory measurements of candidate rock types for deep-crustal reflectors and the Moho to support the thin-layer model as the cause of high-amplitude normal-incidence reflections observed on deep seismic reflection sections.

A total of 108 km of seismic reflection profiling was collected in May and June 1985 by the CALCRUST consortium. The survey was located along five lines in the Ward, Rice, and Vidal Valleys of the eastern Mojave Desert in southeastern California. While the main objective of the survey was to collect high-resolution seismic reflection data from the shallow part of the crust, the consortium was able to augment the main survey with a secondary experiment that resulted in reversed, long-offset, high fold common-midpoint records over a substantial portion of three lines. One of these lines, in the southern Ward Valley, yielded 8 km of reversed common-midpoint gathers spaced at 75 m. Many gathers exceed 100 fold and include offsets beyond 15 km. These data show abundant reflections from the middle and deep crust, and from the Moho, at times from 5.5 to 10 s. Particularly strong reflections can be seen between 5.5 and 6 s, between 7 and 7.5 s, and from the Moho from 8.5 to 10 s. These reflections are easily recognized in a large number of the common-midpoint gathers. They can commonly be traced from the shortest to the longest offsets, even on gathers that have not been enhanced by processing beyond demultiplexing, correlation, and sorting.

Hand-picked examples of deep-crustal reflections were examined for spectral dispersion. Reflections with and without dispersion were found from several areas providing the highest quality data. A strong reflection at 6 s, about 15 km depth, can be identified as a thin layer at many midpoints. The amount of dispersion shows that the layer, a few hundred meters in thickness, must have a velocity at least 10 percent higher than the velocity of the overlying medium. This is also true of many of the other very strong thin-layer reflectors observed. Such a velocity increase in a thin layer is most likely due to the presence of higher-grade metamorphic mineral phases or to a more mafic composition. On the other hand, many strong reflections between 6.8 and 7.6 s do not show dispersion and may result from broad-scale vertical velocity changes at step discontinuities. This suggests that the lower crust, at perhaps 18 km depth, undergoes a change in composition or physical state.

High-quality Moho-depth reflections could be picked on virtually every trace of the Ward Valley data set. These events are grouped into two zones, arriving at about 8.4 and 9.4 s. The earlier reflection does not show dispersion, which is strong on the later arrival. This suggests, along with correlations with regional refraction profiles, that the earlier reflection is due to a step increase in velocity at the top of a high-velocity subcrustal zone. The later arrival is then from the Moho, which is shown to include a layer a few hundred meters thick with a velocity exceeding that of the underlying mantle. This interpretation leads to speculation that such a layer could be the residual from partial melting and extrusion of mantle material or be a zone of highly anisotropic mantle oriented by tectonic mobilization of the Moho.

REFERENCES CITED

Cheadle, M.J., Czuchra, B.L., Ando, C.J., Byrne, T., Brown, L.D., Oliver, J.E., Kaufman, S., 1986, Geometries of deep crustal faults: Evidence from the COCORP Mojave survey, in Barazangi, M., and Brown, L., eds., Reflection seismology: The continental crust: Washington, D.C., American Geophysical Union, Geodynamics Series, v. 14.

Clowes, R.M., and Kanasewich, E.R., 1970, Seismic attenuation and the nature of reflecting horizons within the crust: Journal of Geophysical Research, v. 75, p. 6693-6705.

Dix, C.H., 1965, Reflection seismic crustal studies: Geophysics, v. 30, p. 1068-1084.

Hale, L.D., and Thompson, G.A., 1982, The seismic reflection character of the continental Mohorvicic discontinuity: Journal Geophysical Research, v. 87, p. 4625-4635.

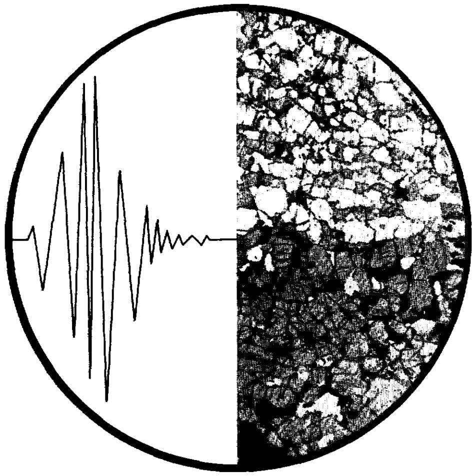
Jones, T.D., 1985, Nature of seismic reflections from the crystalline basement: COCORP Wind River line, Wyoming: Journal of Geophysical Research, v. 90, p. 6783-6791.

Jones, T.D., and Nur, A., 1984, The nature of seismic reflections from deep crustal fault zones: Journal of Geophysical Research, v. 89, p. 3153-3171.

Kosminskaya, I.P., 1964, On layering of the earth's crust: Journal of Geophysical Research, v. 69, p. 802-805.

Meissner, R., 1973, The "Moho" as a transition zone: Geophysical Surveys, v. 1, p. 195.

Deformation, Preferred Orientation and Property Anisotropy in the Continental Lithosphere



CAUSES AND EFFECTS OF ANISOTROPY IN DEFORMED ROCKS

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Plastic deformation of rocks in the crust and in the mantle has been modeled with Arrhenius-type flow laws which relate stress and strain, treating them essentially as scalars and not accounting for the deformation history. This assumption is valid for a limited range of mechanisms, for example, superplastic flow, dislocation climb, and some mechanisms of recrystallization. Wherever dislocation glide is involved in the deformation process, preferred orientation develops which depends on the strain mode, and preferred orientation is present in mantle xenoliths as well as metamorphic tectonites. The development of texture has a profound influence on the stress-strain behavior: (1) It imposes a three-dimensional geometric factor due to crystal orientation which is expressed by the Taylor factor, (2) Strain hardening occurs due to interaction of dislocations in active slip systems, and (3) Latent hardening is expected because of microstructural difficulties in activating inactive slip systems at assumed critical shear stresses. The influence of geometric factors on the plasticity of polycrystals can be approached with the full-constraint Taylor theory (Wenk and others, in press). We observed that for calcite, the effects of strain mode are even stronger than in metals, where the anisotropy of plastic flow was first documented. For example, at low temperature in axial deformation the specimen hardens rapidly, whereas in plane strain it softens during straining. The differences can be attributed to activation of different slip systems (number and relative importance) in each case, particularly the role of mechanical twinning. Wherever dislocation glide is significant and wherever preferred orientation is present, anisotropic flow laws should be considered to explain deformation in geological materials. Particularly emphasized is the importance of deformation experiments in geometries different from axisymmetric compression.

Rocks which have preferred crystallographic orientation, such as mantle xenoliths and many crustal tectonites, do display anisotropy of physical properties. Of particular importance to geophysicists are the anisotropy in thermal conductivity and of acoustic properties. If the texture, given in terms of the three-dimensional orientation distribution function, and the single-crystal properties are known, the properties of the rock can be quantitatively calculated. We have developed analytical expressions for the elastic constants of marble in terms of the elastic constants of the calcite single crystals and the orientation distribution (Johnson and Wenk, in press). The texture is expressed by expanding the distribution function in a series of spherical harmonics (Bunge, 1982; Wenk, 1985). In the case of orthorhombic sample symmetry, only six coefficients of this expansion are needed to fully characterize the elastic properties of the polycrystal when either the Voigt or the Reuss averaging techniques are used.

We have investigated a sample of deformed marble from the Santa Rosa mylonite zone (southern California). The texture is strong (c axes maximum = 6 times random distribution) and the calculated anisotropy of the P-wave velocities is 17 percent. The estimated response agrees with the data, which is closer to the Reuss average than to the Voigt average. Experimental factors influence the resolution. While we have used calcite as an example to demonstrate the method, the same technique can be applied to peridotites that dominate the elastic and plastic behavior of the upper mantle.

REFERENCES CITED

Bunge, H.J., 1982, Texture analysis in materials science: London, Butterworths.

Johnson, G.C., and Wenk, H.R., in press, Elastic properties of calcite polycrystals with preferred orientations (trigonal crystal and orthorhombic specimen symmetry): Journal of Applied Physics.

Wenk, H.-R., 1985, Preferred orientation in deformed metals and rocks: An introduction to modern texture analysis: Orlando, Florida, Academic Press.

Wenk, H.-R., Takashita, T., Van Houtte, P., and Wagner, F., in press, Yield strength and texture development of calcite polycrystals: Journal of Geophysical Research, v. 91, B2.

ASTHENOSPHERE STRUCTURE AND ANISOTROPY BENEATH RIFTS

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From structural studies conducted in ultramafic massifs and in peridotite xenoliths, some unifying concepts are now emerging on the relation between spreading and rifting environments and the nature and structure of the underlying mantle (Boudier and Nicolas, in press; Nicolas, in press). With the exception of some garnet peridotites, all the peridotites reflect in their structure and mineralogy a similar history of ascent in asthenosphere diapirs following paths, specific for each group, through the lithosphere up toward the Earth's surface. The main petrological facies--spinel-lherzolite, plagioclase-lherzolite and harzburgite--define specific groups, within the corresponding massifs, with specific internal organizations, associations, and environments. It is proposed that this diversity arises from a single critical parameter, which is the ascent rate in the asthenosphere diapir. For ascent rates (equated with spreading rates) larger than 1-2 cm/yr, the asthenosphere diapir rises to the depth of the Moho, yielding enough melt to generate a normal oceanic crust with a highly residual harzburgitic mantle. For smaller rates but possibly still larger than 0.5 cm/yr, the asthenosphere diapir meets with the overlying lithosphere at depths <30 km (in the plagioclase lherzolite field) where the melting is stopped. This results in the creation of an oceanic rift with a thinner oceanic crust, possibly replaced by a metasedimentary crust and a plagioclase lherzolite residual mantle. Finally for still smaller ascent rates, the asthenosphere diapir meets with the lithosphere at depths >30 km, resulting in the creation of a continental graben, a limited volcanism, and spinel lherzolite as the residual mantle.

Thus, the mantle signature of a rifting situation with opening rates between 0.5 and around 1 cm/yr is constituted by plagioclase lherzolite like that of Zabargad Island in the Red Sea. The study of solidus plastic deformation in such massifs makes it possible to predict the asthenospheric flow pattern characterizing a rifting environment, provided that the massifs can be reoriented in the framework of rifting. This is possible in an ophiolitic massif like Trinity in the Klamath Mountains (Le Sueur and Boudier, in press), where the limit with the mafic section, equated with the paleo-Moho, provides the horizontal and the strike of the diabase dike swarm provides the rift direction. This also seems possible in Lanzo (western Alps) and Zabargad because the geophysical data suggest in both cases that they represent the head, presumably little tilted, of a much larger mantle intrusion rooted in the mantle.

In these massifs, as well as in a few others where there are no constraints on their primitive attitude (Ojen in southern Spain, Collo in Algeria, Cap Corse in Corsica), the foliation is steep and the flow lineation moderately inclined; this lineation is horizontal in Trinity. The foliation strike is parallel to the Red Sea trend in Zabargad and to the diabase dike swarm attitude in Trinity.

We interpret these data as reflecting a wedge-shaped asthenospheric intrusion below the rift. The steep thermal boundaries between lithosphere and asthenosphere on each side of the rift are due to the small spreading rate. The moderately inclined to horizontal flow lineations indicate that the asthenospheric flow direction is itself inclined. This suggests that the asthenospheric flow diverges from discrete deeper diapirs and that at what are considered shallow depths (5-10 km) it has an important horizontal component parallel to the rift.

The seismic anisotropy below the Rhine graben, which is characterized by the fast velocity being parallel to the graben direction (Fuchs, 1983), is accordingly interpreted as a consequence of the asthenospheric flow being dominantly parallel to the graben direction.

REFERENCES CITED

Boudier, F., and Nicolas, A., 1986, Harzburgite and lherzolite subtypes in ophiolitic and oceanic environments: Earth and Planetary Science Letters, v. 76, p. 84-92.

Fuchs, K., 1983, Recently formed elastic anisotropy and petrological models for the continental subcrustal lithosphere in southern Germany: Physics of Earth and Planetary Interiors, v. 31, p. 93-118.

Le Sueur, E., and Boudier, F., in press, Structure du complexe basique et ultrabasique de Trinity, Californie: Genese d'une ophiolite atypique: Bulletin de la Societe Geologique de France.

Nicolas, A., 1986, A melt extraction model based on structural studies in mantle peridotites: Journal of Petrology, v. 27, p. 999-1022.

CRUSTAL EVOLUTION OF THE RHINEGRABEN AREA: EXPLORING THE LOWER CRUST IN THE RHINEGRABEN RIFT BY UNIFIED GEOPHYSICAL EXPERIMENTS

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Unified geophysical investigations of the lithosphere in the Rhinegraben rift system have revealed new details of the lower crust and its role in the rifting process. The new findings allow to compare four different geophysical notions and properties of the lower crust for their compatibility: (1) The lower crust as the layer beneath the CONRAD discontinuity with a P-wave velocity of about 6.5 km/s or greater (refraction seismics); (2) the laminated band of reflections, as seen in the near-vertical reflection seismic experiments in many parts of the continent; (3) the ductile part of the crust below the brittle-ductile transition, void of earthquakes in seismic active regions; and (4) the electrical conductivity of the lower crust characterizing dry or wet conditions or still unknown conduction phenomena.

In the Rhinegraben area, the lamination of the lower crust serves as an outstanding marker of deep tectonic movements during the rifting process, in which the crust of the Rhinegraben rift system has been subjected to three different natural dynamic processes: (1) Uplift of 2 km to 3 km with subsequent erosion of the Rhinegraben shoulders--Black Forest and Vosges Mountains--caused decompression, possibly leading to the formation of a low-velocity, high-electrical-conductivity zone right on top of the laminated lower crust beneath the elevated shoulders of the Black Forest; (2) the brittle crystalline wedge of the graben proper subsided nearly undeformed into the lower crust, which became about 5 km to 7 km thinner below the graben than below the shoulders; and (3) the deepest hypocenters in the Black Forest (Dinkelberg area), if projected into the neighboring reflection profile, are located 7 km to 8 km within the laminated lower crust beneath the southern Black Forest, indicating a discrepancy between the top of the lower crust as defined by the brittle-ductile transition as seen by the deepest earthquakes, and as defined by the top of the laminated reflection band. The Rhinegraben rift system reveals properties and behavior of the lower crust under a wide variety of tectonic situations.

CRUSTAL STRUCTURE AND TECTONICS IN SOUTHERN CALIFORNIA

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Arrivals from local earthquakes in southern California have given us a look into the seismic structure of the crust. Tomographic and least-squares methods applied to the traveltimes enable us to find velocity and structural variations. Substantial velocity variations exist in both the middle crust and on the Moho discontinuity. The Moho shows almost 10 km of topography and has a substantial anisotropic velocity component to it. Together the results have considerable implications about the mode of tectonic deformation in southern California.

In the middle crust we find that the San Andreas, Garlock, and San Jacinto faults are clearly outlined. The Peninsular Ranges region has correspondingly high velocities that are sharply bounded by the southern San Jacinto fault, underlain by a patch of anomalously slow mantle near San Diego. Comparison with gravity data indicates that these batholiths are very dense. The Mojave Desert, especially the Antelope Valley region, is composed of midcrustal low-velocity material that shows low gravity values. Again, sharp boundaries corresponding to the San Andreas and Garlock faults are indicated. Offshore, the crust thins and higher P_n velocities are found.

The San Jacinto block shows Mojave-type velocities and not Peninsular Ranges-type velocities. San Jacinto Peak may have overridden the Mojave plate on an upper-crustal detachment surface. This accounts for the tremendous height and escarpment of San Jacinto Peak. Also, this overthrusting is helping to develop that portion of the big bend of the San Andreas fault in southern California. In response to this overthrusting, the San Jacinto and Elsinore faults may have developed to alleviate the forces of overthrusting. These faults have little slip relative to the southern San Andreas, but greater seismicity. They do not necessarily extend to Moho depths but may only go to midcrustal detachment surfaces. This would allow the San Andreas at depth to act as the major plate boundary, but at the surface the plate movement could be distributed over several fault zones.

The Transverse Ranges, similar to the San Jacinto Mountains, have no midcrustal expression. They are essentially allochthonous, and the batholiths do not extend into the midcrust. They have been caught in the convergent zone of the San Andreas. The Moho discontinuity shows a local root underneath the eastern Transverse Ranges and a broad root that counterbalances the combined load of the western Transverse Ranges and the topographically high Antelope Valley.

The Salton trough, a region of crustal divergence, shows the high midcrustal velocities that have previously been found by Fuis and others (1982). This high velocity reflects intruded igneous rocks that also underlie the narrow high gravity anomaly in the central trough. The Moho underneath the trough shows a transition from 27-km crust under the Peninsular Ranges eastward to thin 22-km crust under the Colorado River.

The Salton trough has formed by passive pulling apart of the plates and mantle material upwelling to fill the gap.

The thin crust of the Colorado River region corresponds to an area of surface metamorphic core complexes and detachment surfaces. The crust there has undergone extension with the upper crust reacting by brittle fracturing on normal faults and the lower crust reacting by ductile stretching. This separation must occur on detachment surfaces.

A dramatic difference exists between the P_n velocities and the midcrustal P_g velocities; similarly, the topography on the P_n and P_g refractors contrasts. While the P_g velocities show a dramatic velocity contrast across the plate boundary with only a few kilometers of topographic change, the Moho discontinuity shows not only a gross velocity difference between the plates but also substantial topography. The upper crust has reacted brittlely to plate collision. In the lower crust, plate collision forces are diminished by the ductile nature of the rocks. At that depth, the forces of isostasy and mantle convection determine the structure. These two regimes, again, must be separated by detachment surfaces.

The anisotropy found on the Moho is a 0.15 km/s velocity variation with the fast direction at N. 75^o W. Another study of P_n anisotropy in southern California (Vetter and Minster, 1981) found that the fast direction near Pasadena parallels the plate boundary while in the Mojave region no significant anisotropy exists. The gross anisotropy that is found over the array represents an average. It roughly parallels the plate boundary, indicating that it may be stress induced. P_n anisotropy is difficult to interpret since it determines only two of three velocity directions. The vertical dimension generally corresponds to the smallest velocity direction. If sub-Moho material has rotated about any nonvertical axis, this could cause anisotropic variations. P_n anisotropy is found in the oceanic Moho with its fastest horizontal axis perpendicular to the ridge crest (Raitt and others, 1969; Raitt and others, 1971) and its slowest axis vertical. The mantle in California could also have such a stress-induced anisotropy.

REFERENCES CITED

Fuis, G.S., Mooney, W.D., Healy, J.H., Mechan, G.A., and Lutter, W.J., 1982, Crustal structure of the Imperial Valley region, in The October 15, 1979 Imperial Valley earthquake: U.S. Geological Survey Professional Paper 1254, p. 25-50.

Raitt, R.W., Shor, G.G., Francis, T.J.G., and Morris, G.B., 1969, Anisotropy of the Pacific upper mantle: Journal of Geophysical Research, v. 74, p. 3095-3109.

Raitt, R.W., Shor, G.G., and Kirk, H.K., 1971, Mantle anisotropy in the Pacific Ocean: Tectonophysics, v. 12, p. 173-186.

Vetter, U., and Minster, J.B., 1981, P_n velocity anisotropy in southern California: Bulletin of the Seismological Society of America, v. 71, p. 1511-1530.

UPPER MANTLE STRUCTURE BENEATH SOUTHERN CALIFORNIA: OBSERVATION USING SEISMIC TOMOGRAPHY AND INTERPRETATION OF RESULTING FLOW AND STRESS

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We use a tomographic method of inversion of teleseismic P-wave delays recorded using the Southern California Array to determine the three-dimensional structure of the upper mantle beneath southern California (Humphreys and others, 1984). The algorithm employed is a modified form of an algebraic reconstruction technique used in medical X-ray imaging. Deconvolution with an empirically estimated point spread function helps in focusing the image. The inversion assumes an isotropic medium.

The inversion reveals two prominent features. A thin, essentially vertical high-velocity curtain, 2-3 percent faster than the surrounding mantle, lies directly beneath the Transverse Ranges. This feature is wedge-shaped in east-west section, attaining a maximum depth of about 250 km beneath the San Bernardino Mountains. The second feature is a lens of low velocity material, 2-4 percent slow, extending to a depth of about 125 km beneath the Salton Trough.

The seismic rays used in the tomographic inversion are from teleseisms and all traverse the upper mantle beneath southern California at a fairly steep angle. To test the possibility that some of the anomalies may be explained by variations in vertically oriented anisotropy, we use arrivals from two regional sources whose rays intersect the Transverse Range anomaly at moderately shallow angles. The results of this test suggest that anisotropy does not cause the variation in arrival times.

We interpret the features in the upper mantle beneath southern California as being the result of transient small-scale convection. In this model, the high-velocity curtain beneath the Transverse Ranges is a cold blob falling off the base of the lithosphere, and the slow region beneath the Salton trough is the result of penetration of the asthenosphere into the lithosphere. We calculate the flow and stress in the mantle for the (three-dimensional) distribution of density contrasts inferred from seismic tomography by using a simple analytic model with a constant-viscosity mantle underlying a rigid lithosphere. These velocities and stresses might be used to predict a three-dimensional distribution of seismic anisotropy caused by preferred orientation of olivine crystals.

We hypothesize that this convective instability may have been triggered by the rifting that resulted in the opening of the Gulf of California about 5 m.y. ago. We test the validity of this hypothesis by calculating a suite of two-dimensional convection models with temperature-dependent rheologies that use a rifted lithosphere as an initial condition. For certain ranges of parameters, a thin curtain of cold material penetrates to ~250 km depth in about 5 m.y. We plan to compute finite strain fields in this model to determine the anisotropy expected from alignment of crystals by the flow.

REFERENCE CITED

Humphreys, E., Clayton, R.W., and Hager, B.H., 1984, A tomographic image of mantle structure beneath southern California: Geophysical Research Letters, v. 11, p. 625-627.

SYNTHETIC SEISMOGRAM MODELING OF DEEP REFLECTIONS IN THE BASIN AND RANGE PROVINCE

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An unexpected result of deep seismic reflection profiling in the Basin and Range province has been the recognition of a deep zone of subhorizontal discontinuous reflections beneath the entire province (Klemperer and others, 1986; Allmendinger and others, 1987). This reflective zone is always confined to the middle and lower crust except in highly extended areas or "metamorphic core complexes," where it appears to reach shallow levels (Gans and others, 1985; Hurich and others, 1985; McCarthy, 1986). In these areas, uplift and tectonic denudation have been great enough that the reflectivity can be correlated with rocks sampled in drill holes or exposed at the surface.

Reprocessed seismic reflection records from the Picacho Mountains, Arizona, illustrate three features of this unusual reflectivity. (1) The reflections begin at 3.7 km (below a low-angle detachment) and maintain their strength and unusual character to the Moho at a depth of 28 km. The reflection record is seismically transparent beneath the Moho, as it is elsewhere in the Basin and Range. (2) There is a smooth transition from the reflections in the upper and middle crust to those at the Moho. The "reflection" Moho appears to be a Tertiary feature, implying that the shallow reflections are also a by-product of extension. (3) The reflections have similar amplitudes throughout the seismic record, perhaps meaning that the velocity differences between adjacent layers in the shallow and deep crust are similar.

From one- and two-dimensional seismic modeling it is clear that the shallow reflections are coming from many thin layers with alternating high and low velocities. We know this because a 5.5-km-deep drill hole on the flank of the Picacho Mountains provides unparalleled velocity control for the shallow crust. One-dimensional synthetic seismograms based on the velocity log from the well show that the shallow reflections result from subtle velocity differences (approximately 5 percent or less) between adjacent layers. Thus, most reflections are the result of complex interference patterns and are sensitive to velocity changes of individual layers. There are, however, several zones within the well which are strongly reflective and show velocity changes as high as 10 percent. The two-dimensional seismic modeling requires a lateral change in the velocity along a layer to make the reflections discontinuous. Laterally the velocity must vary by 5-10 percent over short distances, but this is consistent with outcrop relationships in the adjacent Santa Catalina Mountains.

The similarity of the shallow reflections with the deeper ones suggests that the source of the deep reflections is also a series of thinly layered high- and low-velocity plates. One of the important implications of this modeling is the presence of relatively isolated zones which are strongly reflective amidst a less reflective matrix. The source of these zones, whose reflection coefficients might approach 0.05, is puzzling. In the vicinity of the drill hole, a plausible explanation for the larger reflections is that they are coming from shear zones that have preferentially concentrated phyllosilicate minerals; that is, they are the result of textural and compositional differences due to extension. The crust in this area could be interpreted as having slipped apart on many surfaces with limited lateral extent. There is evidence for this in wireline logs from the drill hole, which show a strong correlation between low-velocity zones and high gamma ray. (The gamma-ray log essentially reacts to potassium-rich minerals, such as biotite, which might accumulate in slip zones.) Nevertheless, it is unclear at what depth, if any, this source of reflectivity might be replaced by another. As an example, perhaps the deeper part of the seismic record is in fact the result of compositional differences caused by intrusion into the lower crust. Certainly the presence of reflections beneath the Picacho Mountains from 1.5 s to the Moho is an exciting observation indicating that these highly extended areas can serve as windows into the middle crust.

REFERENCES CITED

Allmendinger, R.W., Hauge, T.A., Hauser, E.C., Potter, C.J., Klemperer, S.L., Nelson, K.D., Knuepfer, P., and Oliver, J.E., 1987, Overview of the COCORP 40 °N transect, western United States: The fabric of an orogenic belt Geological Society of America Bulletin, v. 98, p. 308-319.

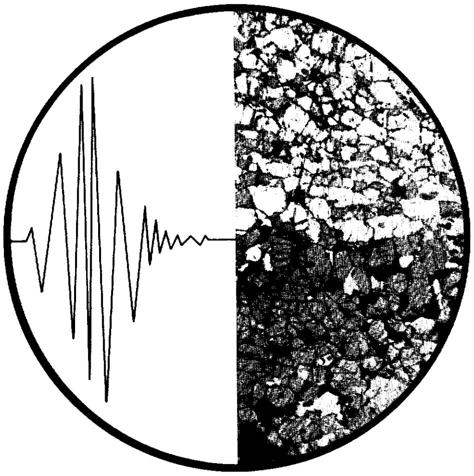
Gans, P.B., Miller, E.L., McCarthy, J., and Ouldcott, M.L., 1985, Tertiary extensional faulting and evolving ductile-brittle transition zones in the northern Snake Range and vicinity: New insights from seismic data: Geology, v. 13, p. 189-193.

Klemperer, S.L., Hauge, T.A., Hauser, E.A., Oliver, J.E., and Potter, C.J., 1986, The Moho in the northern Basin and Range province, Nevada, along the COCORP 40 °N. seismic reflection transect: Geological Society of America Bulletin, v. 97, p.603-618.

Hurich, C.A., Smithson, S.B., Fountain, D.M., and Humphreys, M.C., 1985, Seismic evidence of mylonite reflectivity and deep structure in the Kettle dome metamorphic core complexc Washington: Geology, v. 13, p. 577-580.

McCarthy, J., 1986, Reflection profiles from the Snake Range metamorphic core complex: A window into the mid-crust, in Barazangi, M., and Brown, L., eds., Reflection seismology: The continental crust, Washington, D. C., American Geophysical Union, Geodynamics Series, v. 14, p. 281-292.

Physical State and Processes of the Continental Lithosphere



GEOPHYSICAL IMPLICATIONS OF MANTLE XENOLITHS: EVIDENCE FOR FAULT ZONES IN THE DEEP LITHOSPHERE OF EASTERN CHINA

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We are studying the peridotite xenoliths brought up from the mantle by alkalic basalts that erupted within or near the Tancheng-Lujiang Fault Zone (TLFZ), a major plate-scale rift zone over 2,000 km in length in eastern China. Our objective is to gain some insight into the deformation conditions in the middle and lower continental lithosphere cut by such a fault zone.

TECTONIC SETTING OF THE TANCHENG-LUJIANG FAULT ZONE

Although evidence exists for earlier deformation, the latest deformation phase commenced in the late Mesozoic. Microseismicity continues to the present over much of the TLFZ but moderate to major earthquakes have occurred mainly along its southern half. Alkalic-basaltic volcanism peaked in the latest Tertiary; Pleistocene to Holocene activity suggests that it has not yet ceased. Lastly, abundant geodetic data and geologic observations of deformed Holocene deposits in Shandong Province indicate that tectonic activity continues to the present, with right-lateral fault motion becoming increasingly important in the southern segment. As it is roughly parallel to and contemporaneous with the opening of the Sea of Japan, the TLFZ can be interpreted as a failed marginal basin back-arc from the Japanese subduction zone. The strike-slip motion in the south may reflect the accommodation within the Eurasian plate of the collision with the Indian-Australian plate.

PETROLOGY

Most of the xenoliths are spinel lherzolite, with clinopyroxene typically greater than 10 percent by volume. The compositions of the pyroxenes indicate that these rocks probably originated at depths of 30-80 km where in situ temperatures were 850-1050 ^{o}C.

TEXTURES

Most of the xenoliths display porphyroclastic or granular textures and some are markedly foliated and lineated by the distribution of dark minerals; these are clearly metamorphic tectonites deformed in the mantle. Nodules collected in the vicinity of the TLFZ are significantly finer grained than the ones found well outside the zone; typical recrystallized grain sizes are less than 1 mm. In one volcanic field near Yitong in Jilin Province, we found abundant foliated peridotite ultramylonites with recrystallized grain sizes less than 50 μm. The textures resemble those in crustal shear zones in which shear strains exceed several hundred percent. Straightforward application of the relation between recrystallized grain size in olivine and the applied differential stress suggests that the Yitong mylonites were deformed locally at differential stresses of about 200 MPa.

DEFORMATION STRUCTURES

Preliminary oxidation decoration of some of the fault-zone xenoliths indicates that most of them display dislocation configurations characteristic of diffusion-controlled recovery (a process by which defect damage introduced by deformation is healed). These configurations include cell structure (subgrains) and helical dislocations. These features are commonly found in ultramafic xenoliths from many locations worldwide. In one locality at Nushan Cinder Cone near Jiashan in Anhui Province, we discovered {110} and {100} slip bands, known to occur in great abundance only in environments of shock metamorphism.

CONCLUSIONS

The high strain rates implied by the shock metamorphic features of the Nushan xenoliths suggest that they may have developed as a plastic accommodation of the movements associated with great earthquakes that have occurred along the southern half of the TLFZ. Likewise, we believe that the Yitong mylonite xenoliths are fragments of the TLFZ deep within the continental lithosphere where deformation is accommodated in a ductile fault zone. Since fine grain size and slip bands are readily annealed at basalt magma temperatures, these xenoliths must have been incorporated, transported, and cooled over a short time interval, implying a close temporal connection between the eruptions and the fault movements producing the observed textures and structures. In summary, studies of mantle xenoliths from fault zones offer unique opportunities to investigate the mechanics of faulting in the deep continental lithosphere.

POLYPHASE HISTORY OF ULTRAMAFIC ROCKS IN THE MARBLE MOUNTAINS, NORTHERN CALIFORNIA KLAMATH MOUNTAINS

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The Marble Mountain terrane, a metamorphosed tectonic melange of pre-Middle Jurassic age, consists of middle-amphibolite-facies metasedimentary, metavolcanic, and metamorphosed ultramafic rocks. The latter form numerous fault-bounded bodies ranging from massifs 10 km or more across (such as the Tom Martin and the Seiad massifs) to small, abundant, concordant slivers only a few meters wide. The larger bodies are composed largely of dunite and lesser amounts of harzburgite. At least parts of these bodies are believed to be remnants of mantle peridotite. The smaller bodies are commonly schistose and consist mainly of olivine, talc, antigorite, tremolite, and magnetite, and are considered to be metamorphosed serpentinite (Medaris and others, 1980; Donato, 1985). Petrologic and petrofabric evidence from various textural and compositional types suggests a composite three-phase history of the ultramafic rocks. The earliest phase, ductile deformation of peridotite, is reflected in olivine directional fabrics which indicate high-temperature, low-strain-rate plastic shear flow in the upper mantle (Nicolas and Poirier, 1976). These fabrics are rare or absent in smaller massifs, but are locally common in several of the larger ultramafic bodies in the terrane (Hanks, 1981; Lundquist, 1982; Cannat, 1985; Donato, 1985). The fabrics are commonly overprinted by later recrystallization and deformation features, which are attributed to both mantle and crustal processes. Petrologic data provide evidence of the next phase of evolution and suggest a complex thermal and tectonic history. Metamorphosed rodingites, Ca-metasomatic rocks formed within or adjacent to ultramafic rocks during serpentinization, occur in association with many of the ultramafic rocks in the terrane (Rawson, 1984) and necessitate a low-temperature, hydrous environment early in this phase. Serpentinite and associated rodingite subsequently developed high-temperature, high-pressure metamorphic assemblages indicating conditions near 725 ^{o}C and 0.7 GPa (Rawson, 1984). These high-grade assemblages are now observed in metaserpentinite in the lower structural levels of the melange (Rawson, 1984; Lieberman and Rice, 1983), but occur only locally in the higher structural levels (Donato, 1985). Representative high-grade assemblages in metaperidotite bodies are: olivine+enstatite±anthophyllite, olivine+enstatite+talc±tremolite, and olivine+tremolite+anthophyllite. These assemblages are not isofacial with assemblages in contiguous calcareous, pelitic, mafic, and ultramafic rocks in the higher structural levels of the melange, which contain low-pressure, middle-amphibolite-facies assemblages. Furthermore, many of the high-grade ultramafic assemblages show textural evidence for retrograde metamorphism to middle amphibolite facies. These facts suggest that the high-grade assemblages are products of an early, high-temperature, high-pressure metamorphism which were subsequently overprinted by a later, lower-grade event.

Low-pressure amphibolite-facies metamorphism and contemporaneous isoclinal folding of the assembled melange occurred during the most recent phase of tectonism recognized in the peridotite. The effects of this phase were pervasive in the higher structural levels of the melange, and probably obscured most evidence of earlier events in smaller ultramafic bodies. Continued (renewed?) serpentinization is indicated by probable second-generation metarodingite. Temperatures of metamorphism are estimated to be 500-550 ^{o}C based on garnet-biotite geothermometry and on comparison of assemblages in contemporaneously metamorphosed metapelite, metacarbonate, metabasite, and ultramafic rocks with experimentally determined reaction boundaries. Andalusite in metapelite constrains pressures at 0.3 to 0.5 GPa. Ultramafic assemblages formed at this time are olivine+talc±carbonate, olivine+talc+antigorite, and olivine+talc+tremolite±magnetite.

In summary, three distinct phases of tectonism can be recognized in the ultramafic rocks: (1) High-temperature plastic deformation and recrytallization in the upper mantle, (2) serpentinization in a low-temperature, hydrous regime and subsequent upper-amphibolite-facies metamorphism in the lower crust, and (3) renewed serpentinization followed by low-pressure metamorphism in the upper crust. The first phase of deformation probably reflects plastic flow of upper mantle beneath a pre-Jurassic mid-ocean or marginal basin. The second phase may represent transport of the ultramafic rock from the upper mantle along intra-oceanic thrust faults during the imbrication of the melange. During this phase, ocean-floor sediments and volcanic rocks were tectonically interleaved with partially serpentinized peridotite and subsequently metamorphosed in the lower crust. The third phase of tectonism may have taken place in the region between a subduction zone and the magmatic axis of a Lower to Middle Jurassic volcanic arc, and probably represents the final accretion of the ultramafic rocks to the continental margin.

REFERENCES CITED

Cannat, M., 1985, Tectonics of the Seiad Massif, northern Klamath Mountains, California: Geological Society of America Bulletin, v. 96, p. 15-26.

Donato, M.M., 1985, Metamorphic and structural evolution of an ophiolitic tectonic melange, Marble Mountains, northern California: Stanford, Calif., Stanford University, Ph.D. thesis, 258 p.

Hanks, C.L., 1981, The emplacement history of the Tom Martin Ultramafic Complex and associated metamorphic rocks, north-central Klamath Mountains, California: Seattle, University of Washington, M.S. thesis, 112 p.

Lieberman, J.L., and Rice, J.M., 1983, Prograde metamophism of marble and peridotite in the Seiad Ultramafic Complex, California [abs.]: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 436.

Lundquist, S.M., 1982, Deformation history of the ultramafic and associated rocks of the Seiad Complex, Seiad Valley, California: Seattle, University of Washington, M.S. thesis, 167 p.

Medaris, L.G., Jr., Welsh, J.L., Ferns, M.L., and Kays, M.A., 1980, Prograde metamorphism in the western Paleozoic and Triassic belt, Klamath Mountains province [abs.]: Geological Society of America Abstracts with Programs, v. 12, no. 3, p. 120.

Nicolas, Adolphe, and Poirier, J.P., 1976, Crystalline plasticity and solid state flow in metamorphic rocks: London, Wiley, 444 p.

Rawson, S.A., 1984, Regional metamorphism of rodingites and related rocks from the north-central Klamath Mountains, California: Eugene, University of Oregon, Ph.D. thesis, 252 p.

THE EFFECTS OF WEAK CRUST UPON THE STRENGTH OF THE CONTINENTAL LITHOSPHERE

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Lithospheric strength depends not only upon the presence of intra-lithospheric zones of weakness, but also upon the distribution of these zones and the manner in which intervening competent zones interact. Variability in thickness and lithology of the continental crust therefore provides for a wide range of weakening scenarios.

Since crustal material is generally weaker than upper mantle material at a given temperature, a discontinuity in mechanical properties probably exists across the Moho (Kirby, in press). A general picture emerges therefore of a three-component lithosphere, composed of a strong zone each in the upper crust and upper mantle, separated by a weak lower crust. During flexure, long-term zones of weakness within the crust may be delineated with the aid of a strength index, Σ, which, for a Maxwell material, is defined

$$\Sigma = \frac{\varepsilon_e}{\varepsilon} = 1 - \frac{\varepsilon_v}{\varepsilon}$$

where ε is the total axial strain present in a fiber, and where ε_e and ε_v are the elastic and viscous components of strain, respectively. Strong, predominantly elastic zones exist where Σ is in the neighborhood of 1. Numerical experimentation (DeRito, 1983; DeRito and others, unpubl. data) shows that mechanically weak zones are characterized by strength index values less than about 0.3 (greater than 70 percent viscous strain). The position of rheologic zone boundaries depends, in general, upon time since loading as well as upon temperature and lithologic distribution.

The overall thickness of the lithosphere, h_t, may be defined by the depth to the $\Sigma = 0.3$ isopleth in the upper mantle, or by the depth to a critical isotherm, T_{cm}. The effective thickness, h_e, is the thickness of the elastic plate that best fits a given flexural profile. A weak crust works to weaken the lithosphere as a whole, so that, in general, $h_e < h_t$. Certain modes of interaction may strongly amplify this weakening effect, depending upon the degree of shear coupling between competent layers. Two extreme modes of interaction are: (1) Simple asthenospheric weakening--relative slip between the competent upper crust and upper mantle is negligible, and (2) detachment weakening--negligible shear stress is transmitted across the weak lower crust.

The net weakening effect depends critically upon the position of the weak crustal zone within the lithospheric column as defined by h_t (DeRito and others, 1983). For example, detachment weakening is most effective, reducing h_e by half or more, when the weak zone is centered at depths of about $h_{t/2}$, that is, when the base of the continental crust occurs at mid-lithospheric depths; at these same depths, simple asthenospheric weakening, when operative, may have a negligible effect on h_e. The latter mechanism is most effective when the base of the crust is at depths approaching h_t.

Complete flexural delamination may occur if the isotherm T_{cm} rises to depths shallower than the Moho, or perhaps if the weak zone in the lower crust attains a great enough thickness. In such cases, the upper mantle would not be significantly involved in flexure and the lower crust might behave as a true, buoyant asthenosphere; this is true even in the latter case where the upper mantle remains mechanically competent. Narrow crustal loads may produce unexpectedly broad downwarps due to the small density contrast between the upper and lower crust compared to that between the upper crust and the mantle asthenosphere. The fractional change in flexural wavelength relative to a "normal," mantle-compensated lithosphere, Δ, is

$$\Delta = \sqrt[4]{\frac{\rho_a - \rho_i}{\rho_c - \rho_i}} - 1$$

where ρ_i is the density of basin infill, ρ_a is the density of the mantle asthenosphere, and ρ_c is the density of the crustal asthenosphere. Note that this effect may be appreciable since the density contrast between well-consolidated sedimentary rocks and the less-mafic (weak) constituents of the continental crust may be exceedingly small (Hinze and others, 1978).

Lithospheric flexure generally produces a characteristic gravity signature when the Moho is fully involved (Watts and Cochran, 1974; Karner and Watts, 1983). Flexure in the absence of such a signature may indicate mechanical delamination.

REFERENCES CITED

DeRito, R.F., 1983, The physical meaning and thermal dependence of the thickness of the mechanical lithosphere during flexure: Buffalo, State University of New York, M.S. thesis, 180 p.

DeRito, R.F., Cozzarelli, F.A., and Hodge, D.S., 1983, Mechanism of subsidence of ancient cratonic rift basins: Tectonophysics, v. 94, p. 141-168.

Hinze, W., Bradley, J.W., and Brown, A.R., 1978, Gravimeter survey in the Michigan deep borehole: Journal of Geophysical Research, v. 83, p. 5864-5868.

Karner, G. D., and Watts, A. B., 1983, Gravity anomalies and flexure of the lithosphere at mountain ranges: Journal of Geophysical Research, v. 88, p. 10, 449-50, 472.

Kirby, S. H., in press, Rock mechanic observations pertinent to the rheology of the continental lithosphere and the localization of strain along shear zones: Tectonophysics.

Watts, A.B., and Cochran, J.R., 1974, Gravity anomalies and flexure of the lithosphere along the Hawaiian-Emperor seamount chain: Geophysical Journal of the Royal Astronomical Society, v. 36, p. 57-90.

THERMOBAROMETRY OF ULTRAMAFIC XENOLITHS: STATE OF THE ART AND GLOBAL APPLICATIONS

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Thermobarometry of garnet peridotite xenoliths from kimberlites has become an important means of investigating mantle processes. It is difficult to estimate the accuracy of any thermometer or barometer for application to natural assemblages, however, because of the paucity of absolute references for pressure and temperature in typical garnet lherzolite. The difficulty of testing, and large disagreements in pressure-temperature (P-T) estimates between some thermobarometers, has fostered skepticism of the technique. One requirement for application of thermobarometry to any rock is preservation of mineral compositions that were in chemical equilibrium at some pressure and temperature. It is not possible to prove that any rock has retained such equilibrated compositions, but a necessary condition for equilibration is mineral homogeneity. Xenoliths from kimberlites and other magmas, because they are transported to the surface quickly relative to chemical diffusion times within minerals, are most likely to preserve evidence of the P-T conditions from which they were derived, but even these may be altered or have suffered complex transport histories that in some cases may induce chemical changes that affect P-T estimates.

Unfortunately, the minerals of real rocks are chemically complex, and the results of laboratory experiments cannot be applied as thermobarometers without first accounting somehow for the differences between experimental and natural mineral compositions. Many thermodynamic or empirical corrections schemes have been proposed, so that the potential user of thermobarometers for mantle rocks is faced with making a choice from more than 50 proposed thermometers or barometers!

A suite of chemically homogeneous garnet lherzolite xenoliths from northern Lesotho has been used to test accuracy and precision of a large number of combinations of thermometers and barometers for garnet lherzolite, by comparison of P-T estimates for a diamond-bearing and a graphite-bearing xenolith with the experimentally determined diamond-graphite univariant curve and by comparison of phlogopite-bearing xenoliths to the high-T stability limit of phlogopite. Precision was evaluated by measuring the scatter of P-T estimates for each of four xenoliths from a wide range of P and T when many point analyses of the constituent minerals were used for P-T estimation.

The petrologic criteria for accuracy were not strongly selective for thermometers, but an empirical equation using only reversed data for the enstatite-diopside miscibility gap and incorporating a pressure effect gives minimal scatter and good agreement with petrologic constraints. Of the many formulations of the aluminous enstatite garnet-field barometer, only the original isopleths of MacGregor (1974) yield results in accord with the petrologic constraints, despite more recent, reversed determinations that show the MacGregor isopleths to be slightly erroneous. Evidently, thermodynamic treatments of experimental data, for correction of effects of components present in natural rocks but not in experiments, at their present stages of development unbalance effects that fortuitously compensate in the empirical thermometer and barometer.

Equilibration conditions for suites of garnet lherzolite xenoliths from kimberlites and related rocks from worldwide localities have been determined using the preferred combination of thermometer and barometer. Low-T suites that define paleogeotherms close to the 40 mW/m^2 conductive continental geotherm are characteristic, as are high-T suites of deeper origin that record temperatures higher than the conductive geotherm. Both suites are not present at all localities. The low-T suite in some areas defines a geotherm that is displaced to higher temperatures signifying a higher heat-flow regime, and reflecting the local tectonic environment. The high-T suites characteristically show an origin from a restricted depth range 20 to 40 km wide that may be a reflection of convective or diapiric heat transport and (or) proximity to a magmatic focus.

A gap in P-T space commonly separates low-T from high-T suites at a given locality. This may reflect the presence at depth of materials other than lherzolite, possibly low-Ca garnet harzburgite and (or) magma. The P-T location of intersection of the low-T and high-T suites usually cannot be located accurately because of the gap, but falls between 1,000 and 1,200 °C. This may correlate with the location of the solidus curve for peridotite in the presence of H_2O and CO_2. Both P-T estimates and chemical data are consistent with the interpretation that the transition is the lithosphere-asthenosphere boundary.

High-T peridotite from mobile belts surrounding the Kaapvaal craton in southern Africa originated from depths of 130-170 km, compared to 170-220 km from within the craton, leading to the interpretation that the Kaapvaal craton has a relatively cool root and that the base of the lithosphere shelves from beneath the craton toward the Atlantic and Indian oceans. An analogous relationship derived from fewer localities in North America is interpreted as evidence that the lithosphere-asthenosphere boundary beneath this continent may shelve to the north and south.

A barometer based upon solubility of Ca in olivine coexisting with two pyroxenes, which does not require the presence of an aluminous phase, has been experimentally calibrated (Finnerty and Rigden, 1981). Inasmuch as the inflections observed in geotherms persist when different, independent reactions are employed for thermometers and barometers, they cannot be artifacts of the methods of P-T estimation techniques.

When the olivine barometer is applied to homogeneous spinel lherzolite xenoliths from alkali basalt of San Carlos, Arizona, P-T estimates range from 940 °C, 1.2 GPa to 1070 °C, 2.6 GPa, with a slope of ~8 °C/100 MPa. The lower P limit nearly coincides with the 45-km crustal thickness estimated from seismic waves for the Colorado Plateau, and the high-T, low-slope geotherm is suggestive of anomalous heating of the underlying mantle, consistent with the low shear wave velocity of ~4.5 km/s.

Spinel lherzolite xenoliths from 12 localities in eastern China equilibrated at similar temperatures, but higher pressures than those of San Carlos, defining a P-T slope of ~20 °C/100 MPa. An upper temperature limit of 1,075 °C coincides with that of the San Carlos suite, and with the inflection point observed in garnet lherzolite suites from many localities. More spinel lherzolite geotherms must be estimated to test whether this observation bears significance; for example, could it be related to a temperature-induced change in mechanical properties of mantle rocks?

CRUSTAL GROWTH AND THE LOWER CRUST OF MAGMATIC ARCS

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In magmatic arcs, the common basalt and andesite bodies (and intrusive equivalents) that reach the shallowest arc levels do not originate directly from the mantle (e.g., they are not primary compositions). In the Aleutian arc, we have identified olivine tholeiite as a primary arc lava and have proposed that the early fractionated phases (olivine and clinopyroxene) have accumulated at Moho depth and represent newly formed upper mantle (Kay and Kay, 1985). We have recovered xenolithic fragments that represent direct evidence of these processes (Conrad and Kay, 1984; DeBari and others, in press). The magma composition that results from this fractionation is high-Al basalt, which represents the composition added to the crustal section of the Aleutian arc. More generally, for arcs with even the smallest proportion of high-Al basalt, and especially for arcs with olivine tholeiitic basalts (representing the little-fractionated, near-primary basalt), we find little support for models that assume that crustal additions are andesitic. Shallow-level silicic volcanic and plutonic rocks can be derived by a combination of crystal fractionation from a high-Al basalt and assimilation of a low-melting fraction from the arc crust. The actual crustal section of a particular arc depends on the preexisting crust (oceanic and cratonic are end-members) at the arc magmatic axis, and on the structural response of the arc. But in all cases, the composition of new crustal addition, and in particular the newly added lower crust, is basaltic.

This creates a problem (Kay and Kay, in press), for if the bulk composition of the Earth's continental crust is andesitic, the crustal formation process is not duplicated in present-day arcs. We are left with two choices. First, the mean composition of new crust (non-recycled additions from the mantle to the continental crust) was more andesitic in the past, in particular at the time around 2.5 Ga. when large amounts of crust formed. Second, basaltic continental crust, once formed, is transitory, and returns to the mantle by crustal delamination. A third process, deep subduction of siliceous sediment, might basify crustal composition, but that would only contribute to the problem.

REFERENCES CITED

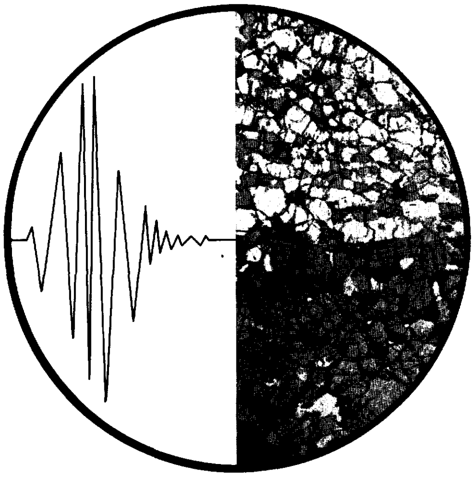
Conrad, W.S., and Kay, R.W., 1984, Ultramafic and mafic intrusions from Adak Island: Crystallization history, and implications for the nature of primary magmas and crustal evolution in the Aleutian Arc: Journal of Petrology, v. 25, p. 88-125.

DeBari, S., Kay, S.M., and Kay, R.W., in press, Xenolithic evidence for the nature of the crust-mantle boundary and primitive magmas in the Aleutian arcs: Journal of Geology.

Kay, S.M., and Kay, R.W., 1985, Role of crystal cumulates and the oceanic crust in the formation of the lower crust of the Aleutian arc: Geology, v. 13, p. 461-464.

Kay, R.W., and Kay, S.M., in press, Petrology and geochemistry of the lower continental crust: Journal of the Geological Society of London.

Chemical and Physical State of the Mantle Related to the Transport and Reactions of Fluids and Melts



DISSOLUTION OF VOLATILES IN MANTLE OLIVINE: RHEOLOGICAL IMPLICATIONS

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The evidence is overwhelming that volatiles remain in the Earth's mantle. Xenoliths of mantle rocks accidentally incorporated in volcanic eruptions ubiquitously display fluid bubbles on healed cracks within olivine and pyroxene crystals (see Roedder, 1965). Analyses of these bubbles repeatedly have shown that they are virtually pure CO_2, with trace amounts of noble gases. Similarly, volatile emanations accompanying volcanic eruptions are rich in CO_2. Although H_2O also is a major component of such gases, isotopic studies argue strongly that the water is a crustal contaminant (see I. Barnes, this volume). Xenoliths from kimberlite pipes always have their grain boundaries serpentinized, but isotopic studies have shown that this water also is crustal contamination. Many of these xenoliths, however, contain phlogopite that clearly is part of the mantle paragenesis and has a mantle isotopic signature. On the other hand, analyses of "hydrous" minerals in xenoliths from oceanic and tectonic areas usually show them to be oxyamphiboles and fluorphlogopites. Thus, a variety of independent lines of evidence demonstrates the existence of CO_2 in the mantle, but, except for the subcontinental lithosphere, the evidence for H_2O is weak.

For 15 years, I have been collecting evidence that some volatile species dissolve in mantle olivine and precipitate as submicroscopic fluid bubbles during solid diapirism preceding incorporation of xenoliths in alkalic basalt (Green and Radcliffe, 1975) or during transportation of xenoliths to the surface in kimberlite (Green and Gueguen, 1983). Direct evidence for the contents of the fluid precipitates has been lacking except that they commonly display an amorphous phase on their surfaces that contains carbon. Precipitated bubbles in fresh olivine do not have serpentine on their surfaces, nor do rare recrystallized olivine grains contained within olivine porphyroclasts and thereby isolated from the late-stage (crustal) serpentinization of the grain-boundary network. Whatever is the nature of the fluid, bubble densities indicate a solubility up to several hundred parts per million at depths in excess of 100 km.

Recent experimental evidence from my laboratory indicates the following: (1) Olivine equilibrated with CO_2 dissolves no carbon at low pressure (0.1 GPa, 1200 ^oC), but dissolves of the order of 100 wt ppm at 3.0 GPa, 1200 ^oC (Tingle and others, 1985); (2) experimental deformation of a dry synthetic harzburgite in the range 1.0-3.0 GPa, 1,100-1,400 ^oC displays a marked pressure dependence (activation volume ~30 cm^3/mole). Extrapolation of these data to conditions approximating the base of the olivine-bearing mantle (13 GPa, 1,500 ^oC, τ = 0.1-1 MPa) predicts a strain rate of 10^{-21} s^{-1} (Green and Hobbs, 1984); (3) a single experiment conducted at 1200 ^oC, 3.0 GPa, in which olivine was equilibrated with carbonate, yielded a strength about half of the volatile-free value (R. Borch and H.W. Green, unpub. data).

Experimental data from several laboratories over 20 years have demonstrated that dissolution of small amounts of H_2O weakens olivine by a factor of 2 or more (see Mackwell and others, 1985). These results, coupled with the new data summarized above, suggest that dry olivine is too strong to be consistent with plate tectonics; dissolution of H_2O or CO_2 in olivine probably is responsible for flow of peridotite at stress levels present in the mantle. The evidence for volatiles in the mantle suggests that CO_2 is the more likely choice, but more experimental data are needed to confirm carbon-induced weakening.

REFERENCES CITED

Green, H.W., and Gueguen, Y., 1983, Deformation of peridotite in the mantle and extraction by kimberlite: A case history documented by fluid and solid precipitates in olivine: Tectonophysics, v. 92, p. 71-92.

Green, H.W., and Hobbs, B.E., 1984, Pressure dependence of creep in dry polycrystalline olivine: Eos, Transactions, American Geophysical Union, v. 65, p. 1107.

Green, H.W., and Radcliffe, S.V., 1975, Fluid precipitates in rocks from the earth's mantle: Geological Society of America Bulletin, v. 86, p. 846-852.

Mackwell, S.J., Kohlstedt, D.L., and Paterson, M.S., 1985: The role of water in the deformation of olivine single crystals: Journal of Geophysical Research, v. 90, p. 11,319-11,334.

Roedder, E., 1965, Liquid CO_2 inclusions in olivine-bearing nodules and phenocrysts from basalts: American Mineralogist, v. 50, p. 1746-1782.

Tingle, T.N., Green, H.W., and Finnerty, A.A., 1985: The solubility and diffusivity of carbon in olivine: Eos, Transactions, American Geophysical Union, v. 66, p. 1135.

MANTLE DEGASSING, MANTLE CONVECTION, AND VOLCANISM

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Carbon dioxide (CO_2) discharges throughout the world correspond to zones of seismic activity. Volcanoes characteristically occur in the seismically active zones. Isotopic compositions show that the $^{13}CO_2$ is from the mantle in some places. CO_2 may be a cause for mantle convection. Discharge of CO_2 on spreading centers leads to the suggestion that CO_2 may be a causative factor in seafloor spreading.

INTRODUCTION

A compilation of carbon dioxide (CO_2) discharges throughout the world shows that CO_2 discharges occur in zones of seismicity (Barnes and others, 1984). Active volcanism occurs in these same seismically active zones. This fact led to an examination of the sources of volatiles in volcanic terranes to determine which if any of the volatiles are of magmatic origin in the strictest sense.

There is a great deal of confusion about the relative importances of amounts and sources of volatiles in volcanic eruptions. Much of the confusion may stem from the occurrence of clouds during volcanic eruptions that reach the atmosphere. Because most atmospheric clouds are composed of water droplets, there is an intuitive identification of the clouds above erupting volcanoes as "steam" clouds even in the absence of any data (Christiansen and Peterson, 1981). The intuitive belief in "steam" clouds is reinforced by the large number of studies of fumaroles that show steam to be the most abundant component of fumarolic gases (Gerlach, 1980). In the most detailed and careful analyses of fumarolic gases to date, it was shown that fumarolic gases are in chemical equilibrium (Giggenbach, 1980). The demonstration that volcanic gases are in internal chemical equilibrium is of great importance but does not show the origins of any of the volatile components.

VOLATILES FROM RECENT ERUPTIONS

Recent eruptions in Alaska and Washington (Christiansen and Peterson, 1981) have offered opportunities to study the chemical and isotopic compositions of volcanic volatiles and to identify the sources of the volatiles. The similarity in major component compositions of fumarolic gases from Mount St. Helens and Erta'Ale and the continuum they form with other fumarolic gases (Gerlach, 1980) show that an explanation for one will probably serve as an explanation for all. The gases are approximately 80 percent steam, 10 percent CO_2 and equilibrium amounts of H_2S, SO_2, H_2, CO, HCl and less abundant gases such as COS. Isotopic evidence is essential to determine the sources of the H_2O and CO_2; chemical evidence is sufficient to show the source of chloride that provides the HCl. Metamorphic brines occur both at the site of two explosive volcanic eruptions in Alaska and in the metamorphosed volcanic rocks near Mount St. Helens. The major analyses are repeated here in table 2. The term "metamorphic brine" refers to the waters, rich in chloride, that are present during the reactions that produced the metamorphic rocks. The brine near Mount St. Helens, for example, is supersaturated with respect to the minerals (albite, potassium feldspar, calcite, quartz, and chlorite) that constitute the metamorphosed volcanic host rock of the Eocene Ohanapecosh Formation. The $^{87}Sr/^{86}Sr$ data show that the brine (0.7033), calcite (0.7032), and silicates (0.7036) are genetically related. The metamorphic brines may explain the common reports of chloride in fumarolic discharges because, at temperatures in excess of 300 ^{o}C, hydrochloric acid is very slightly ionized and the undissociated hydrogen chloride is sufficiently volatile to make condensates quite acid. Condensate from fumarolic gases in the crater of Mount St. Helens had a pH of 0.8 and was 0.2N solution of HCl. If the metamorphic brines contribute appreciably to volcanic eruptions, very acid rain rich in chloride would result. No such rain was found after the eruption of Mount St. Helens, so steam from the brine was not a major volatile during the eruption, although such steam constitutes 80 to 87 percent of the gas from the fumaroles. Seawater with 19,000 mg/L chloride would behave very much the same as the metamorphic brines.

SOURCE OF CO_2

Of the anhydrous gases at Mount St. Helens and the locality of the two recent volcanic explosions in Alaska, CO_2 is the major component. Anhydrous carbon dioxide is the gas found in fluid inclusions in deep-sea basalts both in the Atlantic (Pineau and others, 1976) and Pacific (Moore and others, 1977) Oceans. The isotopic compositions of the CO_2 in the fluid inclusions, -4.7 to -8.1 per mil (PDB), gives a guide to the isotopic compositions of CO_2 from the mantle. The isotopic composition of the CO_2 from the explosion pits in Alaska is -6.36 per mil, midrange for mantle CO_2, and the CO_2 from Mount St. Helens (-10.7 per mil) is close to the range fixed by deep-sea fluid inclusions. Dissolved CO_2 (-3.0 per mil) and gaseous CO_2 (-4.2 per mil) from San Miguel, Azores may also be from the mantle as is the CO_2 (-5.7 per mil) discharging at Chaves, Portugal (de Almeida, 1982). CO_2 from the mantle (-5.0 to -8.4 per mil) also discharges from the active spreading center of Iceland. CO_2 of mantle origin (-4.0 to -5.1 per mil, Taylor and others, 1967) also discharges in the Eifel District, West Germany, the type locality of maars and "phreatic" eruptions (Steininger, 1819; Schmincke, 1977). CO_2 of mantle origin (-6.5±0.5 per mil) also discharges from Erta'Ale volcano in Ethiopia (Allard and others, 1977), Asal, -4.8 to -5.9 per mil (Allard, 1980), Usu volcano, Japan, -4.4 per mil (Allard, 1981b), Krakatoa, Indonesia, -7.0 per mil (Allard and others, 1981) and Soufriere, Antilles, -5.5 per mil (Allard, 1981a). Other volcanoes also discharge CO_2, although the isotopic compositions are not yet known. The Canary Islands (Ramon-Vasallo, written commun.) and Philippine Islands (Feliciano, 1926) are examples. Carbon dioxide also discharges from submarine spreading centers as at the Galapagos (Corliss and others, 1979), but, of course, is much more difficult to detect than CO_2 from subaerial volcanoes because of the solubility of CO_2 in seawater.

Although CO_2 discharges seem ubiquitous from volcanoes and spreading centers, the CO_2 is not always accompanied by silicate melts; indeed, CO_2 discharges last for millenia unaccompanied by melts (Barnes and others, 1984). If CO_2 discharges in the absence of lava, then the CO_2 pressure (not fugacity) must equal or exceed the total pressure at the source of the CO_2. From isotopic and tectonic evidence, the source in some places must be the mantle. Thus it must be concluded that the mantle contains a free CO_2 gas phase. The CO_2 is buoyant, because at no temperature or pressure does the density (Kennedy and Holser, 1966) of CO_2 equal that of a silicate melt. If the gas is buoyant, so must be gas-melt mixtures in the mantle, leading to convective movement without the requirement of addition of heat to the convective system. The convective upwelling provides a mechanism for seafloor spreading.

REFERENCES CITED

Allard, P., 1980, Caracteristiques geochimiques des volatiles emis par l'eruption volcanique de Novembre 1978, dans le Rift d'Asal: Bulletin Societe Geologique France, v. 22, p. 825-830.

Allard, P., 1981a, Composition chimique et isotopique des gaz emis par le nouveau dome andesitique de la Soufriere de Saint-Vincent (Antilles): Comptes Rendus Academie Sciences Paris, v. 293, ser. 2, p. 721-724.

-----1981b, Composition isotopique du carbone dans les gaz d'un magma dacitique (Volcan Usu, Japon). Relation entre le rapport $^{13}C/^{12}C$ des volatils et le rapport $^{87}Sr/^{86}Sr$ de la phase silicatee dans le volcanisme d'arc: Comptes Rendus Academie Sciences Paris, v. 293, ser. 2, p. 583-586.

Allard, P., Jehanno, C., and Sabroux, J.C., 1981, Composition chimique et isotopique des produit gazeux et solides de l'activite eruptive du Krakatoa (Indonesie) pendant la periode 1978-1980: Comptes Rendus Academie Sciences Paris, v. 293, ser. 2, p. 1095-1098.

Allard, P., LeGuern, F., and Sabroux, J.C., 1977, Thermodynamic and Isotopic Studies in Eruptive Gases: Geothermics, v. 5, p. 37-40.

Barnes, I., Irwin, W.P., and White, D.E., 1984, World distribution of carbon dioxide springs and major zones of seismicity: U.S. Geological Survey Miscellaneous Investigations Series Map I-1528, 10 p.

Christiansen, R.L., and Peterson, D.W., 1981, Chronology of the 1980 eruptive activity, in Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 17-30.

Corliss, J.B., Dymond, J., Gordon, L.I., Emond, J.M., VonHerzen, R.P., Ballard, R.D., Green, K., Williams, D., Bainbridge, A., Crane, K. and Van Andel, T., 1979, The submarine thermal springs on the Galapagos Rift: Science, v. 203, p. 1073-1083.

de Almeida, F.M., 1982, Novos dados geothermometicos sobre aguas de Chaves e de S. Pedro do Sul [New geothermometric data on the waters of Chaves and S. Pedro do Sul): Comunicacoes dos Servicos Geologicos de Portugal, v. 68, p. 179-190.

Feliciano, J.M., 1926, A study of the thermal springs in the Philippines: Proceedings Third Pan Pacific Science Congress, Tokyo, v. 1, p. 804-811.

Gerlach, T.M., 1980, Interpretation of volcanic gas data from tholeiitic and alkaline lavas, preliminary study and interpretation of magmatic gas, in La Guern, F., ed., Programme interdisciplinaire de recherche

sur la preveion et la surveillance des eruptions volcaniques, Bulletin 31: Gif-sur-Yvett, France, p. 69-92.
Giggenbach, W.F., 1980, Geothermal gas equilibria: Geochimica et Cosmochimica Acta, v. 44, p. 2021-2032.
Kennedy, G.C., and Holser, W.T., 1966, Pressure-volume-temperature and phase relations of water and carbon dioxide, in Clark, S.P., Jr., ed., Handbook of physical constants, revised edition: Boulder, Colo., Geological Society of America, Memoir 97, p. 371-383.
Moore, J.G., Batchelder, J.N., and Cunningham, C.G., 1977, CO_2-filled vesicles in mid-ocean basalt: Journal of Volcanology and Geothermal Research, v. 2, p. 309-327.
Pineau, F., Javoy, M., and Bottinga, Y., 1976, $^{13}C/^{12}C$ ratios of rocks and inclusions in popping rocks of the Mid-Atlantic Ridge and their bearing on the problem of isotopic composition of deep-seated carbon: Earth and Planetary Science Letters, v. 29, p. 413-421.
Schmincke, H-U, 1977, Phreato magmatsche Phasen in Quartaren Vulkanen der Osteifel [Phreatomagmatic phases in Quaternary volcanoes of East Fifel]: Geologisches Jahrbuch Series A, v. 39, p. 3-45.
Steininger, D.J., 1819, Geognostiche Studien am Mittelrheine [Geologic Studies in the Middle Rhine]: Mainz, F. Kupferberg, 223 p.
Taylor, H.P., Jr., Frechen, J., and Degens, E.T., 1967, Oxygen and carbon isotope studies of carbonatites from the Laacher See district, West Germany and the Alno district, Sweden: Geochimica et Cosmochimica Acta, v. 31, p. 407-430.

TABLE 2. *Results of analyses of brines from the Alaska Peninsula and Mount St. Helens*

	Alaska Peninsula	Mount St. Helens
pH (units)	5.9	8.34
T (°C)	52.8	8
Species (mg/L)		
SiO_2	120	9.2
Ca	1,500	7,100
Mg	460	5.5
Na	17,700	6,100
K	450	6.9
HCO_3	1,240	18.0
SO_4	140	280.0
Cl	32,000	22,000
B	360	3.0
Isotope ratio (per mil SMOW)		
δD	-37.9	-43.4
$\delta^{18}O$	+.42	-4.29

SOLID AND FLUID INCLUSIONS IN MANTLE XENOLITHS: THEIR ORIGINS AND IMPLICATIONS FOR THE PROPERTIES OF THE MANTLE

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Solid and fluid inclusions in mantle xenoliths aid in distinguishing between the chemical and physical effects of processes taking place within the mantle and those resulting from decompression events and alteration during ascent of the xenoliths to the earth surface. Studies of ultramafic massifs and composite xenoliths show that magmas may react with Mg-rich wallrocks in the upper mantle, altering the wallrock to more Fe-rich compositions. This alteration process is commonly called "mantle metasomatism." Previous investigations suggest that mantle metasomatism is carried out by fluids that evolve from magmas and react with the peridotite wallrocks to produce compositional variations in minerals as a function of distance from the dikes (Wilshire and others, 1980; Andersen and others, 1984; Menzies and others, 1985; Nielson and Noller, in press). Criteria on separating mantle dike--wallrock reactions from xenolith--host basaltic magma interaction during ascent have been gathered from the study of grain coatings, intragranular inclusions, and fluid inclusions in (composite) mantle xenoliths (Rocchia, 1982; Green and Gueguen, 1983; Noller, 1986).

Composite ultramafic xenoliths rimmed by kaersutite selvages (dikes) from southwestern United States and France contain four types of solid and fluid inclusions. Three types of solid inclusions are spinel inclusions, amphibole glass, and basalt glass. Spinel inclusions consist of trails of dark spinel octahedra (up to 20 µm), aligned along parallel lines approximately 20 µm to 50 µm apart, and their abundance gradually decreases away from kaersutite selvages. Amphibole glass consists of clear films, containing fluid inclusions, with dendritic and honeycomb morphologies along grain boundaries and fractures. These films branch from reaction rims around amphiboles in both kaersutite selvages and lherzolite. Basalt glass typically consists of brown and black films that line cleavages and fractures and, to a lesser degree, grain boundaries in the xenoliths. Basalt-glass films are ubiquitous throughout most mantle xenoliths, indicating that basaltic magmas interact with xenolith interiors to a great extent.

These three types of solid inclusions can be used to discriminate between actual mantle processes and processes acting upon a fragment of mantle as it is entrained and carried to the Earth's surface by the basaltic magma. The spinel inclusions are interpreted to have formed by a process associated with the emplacement of kaersutite dikes in the mantle; thus, these inclusions are important indicators of fluid compositions in the mantle. Amphibole glass probably was derived from "flash" melting of amphibole during decompression in the host basaltic magma during rapid ascent (Switzer and Melson, 1969; Francis, 1976). This hypothesis is supported by the observations that (1) amphibole glass is present in fractures unoccupied by spinel inclusions, and (2) amphibole grains have honeycomb-textured boundaries infilled with amphibole glass. The fractures apparently formed from expansion and fracturing of the xenoliths as decompression occurred. Continuous decompression expansion of the xenoliths opened the way for injection of both decompression melts and host basalt without total disaggregation of the xenoliths.

Fluid is present as inclusions in amphibole glass and as planes of secondary inclusions in the xenoliths that locally branch from basalt injections. Thermometric analyses of fluid inclusions in xenoliths from Dish Hill, California, indicate that they are composed of essentially pure CO_2, which is consistent with other fluid inclusion studies (Roedder, 1965; Pasteris, in press). These inclusions have densities of 0.93 to 0.40 g/cm^3, which indicate filling pressures of 0.2-0.7 GPa at crustal depths of 9-26 km. However, the fluid in these inclusions may not be representative of the fluid present at the time of their entrapment (Mathez and Delaney, 1981; Pasteris, in press). The range in the densities of these CO_2 inclusions is interpreted to represent continuous entrapment of fluid during ascent.

Solid and fluid inclusions are important sites of incompatible-element concentrations in mantle xenoliths. Thus, scientists who study mantle rocks are confronted with an analytical dilemma: laboratory leaching of xenolith samples before analysis may destroy inclusions that are carrying intrinsic mantle components, whereas failure to leach the samples probably leaves a host-rock contaminant. It is apparent from detailed maps of xenoliths containing basalt glass that it may be difficult to uniquely identify mantle trace-element compositions with whole-rock analysis. In addition, measurements of physical properties also are affected. There are, for example, problems in determining magnetic properties of the lower lithosphere by using xenoliths, and careful petrographic work must be performed prior to analysis. The precipitation of Fe-oxides from decompression melts and exsolution of metals (Fe and Ni) during ascent can produce a post-entrainment magnetization that does not represent lower lithospheric conditions (Garcia-Spatz and Wasilewski, 1985).

REFERENCES CITED

Andersen, T., O'Reilly, S.Y., and Griffin, W.L., 1984, The trapped fluid phase in upper mantle xenoliths from Victoria, Australia: Implications for mantle metasomatism: Contributions to Mineralogy and Petrology, v. 88, p. 72-85.

Francis, D.M., 1976, The origin of amphibole in lherzolite xenoliths from Nunivak Island, Alaska: Journal of Petrology, v. 17, p. 357-378.

Garcia-Spatz, R., and Wasilewski, P., 1985, Magnetic properties of mantle xenoliths and ilmenite nodules and the magnetic character of the upper mantle [abs.]: Eos, Transactions, American Geophysical Union, v. 66, no. 18, p. 380.

Green, H.W., and Gueguen, Y., 1983, Deformation of peridotite in the mantle and extraction by kimberlite: A case history documented by fluid and solid precipitates in olivine: Tectonophysics, v. 92, p. 71-92.

Mathez, E.A., and Delaney, J.R., 1981, The nature and distribution of carbon in submarine basalts and peridotite nodules: Earth and Planetary Science Letters, v. 56, p. 217-232.

Menzies, M.A., Kempton, P.D., and Dungan, M., 1985, Interaction of continental lithosphere and asthenospheric melts below the Geronimo

volcanic field, Arizona, U.S.A.: Journal of Petrology, v. 26, pt. 3, p. 663-693.
Nielsón, J.E., and Noller, J.S., in press, Processes of mantle metasomatism: Constraints from observations of composite peridotite xenoliths, in Mullen, E.D., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Boulder, Colo., Geological Society of America Special Paper 215.
Noller, J.S., 1986, Solid and fluid inclusions in mantle xenoliths: An analytical dilemma?: Geology, v. 14, p. 437-440.
Pasteris, J.D., in press, Fluid inclusions in mantle xenoliths, in Nixon, P., ed., Mantle xenoliths: London, Wiley.
Rocchia, J., 1982, Interactions entre nodules de peridotites et basaltes-hotes: Exemples de l'Ardeche et des Causses: Paris University, doctoral thesis 3d cycle, 127 p.
Roedder, E., 1965, Liquid CO_2 inclusions in olivine-bearing nodules and phenocrysts from basalts: American Mineralogist, v. 50, p. 1746-1782.
Switzer, G., and Melson, W. G., 1969, Partially melted kyanite eclogite from the Roberts Victor Mine, South Africa: Smithsonian Contributions to the Earth Sciences, no. 1, 9 p.
Wilshire, H.G., Nielson-Pike, J.E., Meyer, C.E., and Schwarzman, E.L., 1980, Amphibole-rich veins in lherzolite xenoliths, Dish Hill and Deadman Lake, California: American Journal of Science, Jackson Volume, v. 280-A, p. 576-593.

FLUID-WALLROCK INTERACTIONS IN THE MANTLE: EVIDENCE FROM COMPOSITE LHERZOLITE-HORNBLENDITE XENOLITHS

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Metasomatic reactions between magmatic hornblendite veins and their peridotite wallrocks have been well documented by systematic major- and minor- element analyses of minerals in the peridotite (Wilshire and others, 1980). Additional whole-rock major-, minor-, and trace-element data on the nature of the reactions are reported here. Sample Ba-2-1, from the Dish Hill, California basanite cone, is a large (17 cm in largest dimension) composite xenolith of spinel lherzolite with a hornblendite selvage 1 to 9 mm thick at one end. The selvage, which contains about 5 percent biotite and 5 percent apatite in addition to Ti-rich pargasite, has been shown to be a dike emplaced in the mantle (Wilshire and Trask, 1971).

Systematic data derived from Ba-2-1 include major element compositions of minerals (Wilshire and others, 1980) and whole-rock volumes (reported here) sampled at increasing distance from the selvage, chondrite-normalized rare earth element (REEcn) contents of the same whole-rock volumes (reported here), and REE and Nd-Sr isotopic compositions of both clinopyroxene separates from the lherzolite (location unknown) and amphibole from the dike selvage (Menzies and others, 1985).

The systematic analyses all show that lherzolite bulk and mineral compositions are richer in Fe, Na, K, Ti, and Mn in a 4-cm-wide zone adjacent to the hornblendite dike than are minerals and volumes of lherzolite farther from the dike. In the contact zone the bulk rock also has higher H_2O^+ and CO_2 than the rock volumes farther from the dikes, and light REEcn (LREE) are enriched relative to heavy REEcn (HREEcn) so that the ratio LREE/HREEcn is greater than 1.0. This REE pattern is like that of the selvage amphibole, but the REEcn abundances are much less in the bulk rock. The systematic data show that compositional variations of the minerals were caused by reaction between the lherzolite and fluids from which the hornblendite crystallized. Bulk chemical variations also are due in part to introduced amphibole and solid inclusions (Nielson and Noller, in press); the abundances of both systematically decrease with distance from the hornblendite dike.

Published compositions of unlocated clinopyroxene separates from Ba-2-1 showed LREE/HREEcn less than 1.0 and Nd-Sr isotopic compositions that are highly depleted compared to amphiboles from the dike (Menzies and others, 1985). The whole rock compositional variations reported here raise questions about these data, because they indicate that clinopyroxene REE and isotopic compositions likely vary with proximity to the hornblendite dike. Clinopyroxene separates (unlocated) from Ba-1-72, another Dish Hill composite sample, have LREE/HREEcn greater than 1.0, and isotopic compositions similar to amphibole of the dikes. The strong similarities between Ba-2-1 and Ba-1-72 further suggest that data on unlocated separates may be misleading. For example, in both Ba-2-1 and

Ba-1-72, major-element mineral compositions vary with proximity to the hornblendite, and the REE composition of the hornblendite dikes are identical. The only physical difference between the two samples is that Ba-1-72 is a thin (7 cm) slab of lherzolite sandwiched by two hornblendite dikes and Ba-2-1 is a large mass of lherzolite with a dike at one end. Thus, Ba-1-72 lherzolite is likely to have been completely soaked by dike fluids, and the minerals more extensively metasomatized (Nielson and Noller, in press). However, the apparent differences in REE and isotopic compositions led Menzies and others (1985) to separately classify the samples and to infer an entirely different history for each sample.

The systematic whole rock REE compositions reveal two important facts: (1) The pattern of LREEcn-enrichment is directly related to proximity to the hornblendite, and thus is due to a process of mantle metasomatism, regardless of whether the LREE occupy clinopyroxene structural sites or occur in inclusions within and around other minerals. (2) The REEcn pattern of the volume of rock adjacent to the dike is like that characteristic of metasomatized peridotite xenoliths from many worldwide localities (Frey and Green, 1974). Like the Dish Hill composite xenoliths, these other metasomatized peridotites show enrichment of Fe and associated elements, LREE enrichment relative to HREE, and some contain hydrous secondary minerals. These features commonly are ascribed to processes acting over large regions of the mantle. These processes are believed to be necessary precursors to alkali basalt magmatism (see Wilshire, in press). Evidence from the Dish Hill xenoliths indicates that the processes of local metasomatism consequent upon intrusion of volatile-rich melts, and the postulated regional metasomatic processes of unspecified origin must mimic one another, or the origin of samples that lack structural context has been misinterpreted.

REFERENCES CITED

Frey, F.A., and Green, D.H., 1974, The mineralogy, geochemistry, and origin of lherzolite inclusions in Victoria basanites: Geochimica et Cosmochimica Acta, v. 38, p. 1023-1059.

Menzies, M.A., Kempton, P.D., and Dungan, M.A., 1985, Interaction of continental lithosphere and asthenospheric melts below the Geronimo volcanic field, Arizona, U.S.A.: Journal of Petrology, v. 26, p. 663-93.

Nielson, J.E. and Noller, J.S., in press, Processes of mantle metasomatism: Constraints on interpretations from composite peridotite xenoliths, in Mullen, E.D., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Boulder, Colo., Geological Society of America Special Paper 215.

Wilshire, H. G., in press, A model of mantle metasomatism, in Mullen, E.D., and Pasteris, J.D., eds., Mantle metasomatism and alkaline magmatism: Boulder, Colo., Geological Society of America Special Paper 215.

Wilshire, H.G., Pike, J.E.N., Meyer, C.E., and Schwarzman, E.C., 1980, Amphibole-rich veins in lherzolite xenoliths, Dish Hill and Deadman Lake, California: American Journal of Science, v. 280-A, Jackson Volume, Part 2, p. 576-593.

Wilshire, H.G. and Trask, N.J., 1971, Structural and textural relationships of amphibole and phlogopite in peridotite inclusions, Dish Hill, California: American Mineralogist, v. 56, p. 240-255.

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