

Lithosphere-asthenosphere boundary

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A Penrose Conference on the topic of the lithosphere-asthenosphere boundary was convened in Vail, Colorado, on November 16–21, 1975. The conference was motivated by a proposal submitted to the Geological Society of America by the U.S. Geodynamics Committee in January 1975. The 67 participants, 14 from outside the United States, were Earth scientists representing a broad spectrum of disciplines including geodesy, rheology, seismology, geochemistry, petrology, and tectonophysics.

The idea behind the conference was to focus on one feature of the mantle central to the understanding of plate dynamics. It has been known since the work of Barrell and others in the early part of this century that there exists a transition region at about 100-km depth which separates a lithosphere capable of withstanding long-term nonhydrostatic stresses from a more plastic asthenosphere where the flows associated with isostatic adjustments take place. In the light of modern plate tectonic theory, this lithosphere-asthenosphere boundary is viewed with new significance: a popular premise is that it coincides with the base of the plates, capping a region of the mantle where the shear strains associated with plate motions are concentrated. This shear zone is often identified with the Gutenberg low-velocity zone, thought by seismologists to be partially molten, and is often characterized as being quite narrow, perhaps extending to only 200-km depth. These notions complement nicely the dynamical theories that invoke as the main driving force the negative buoyancy of the plates themselves (Elsasser models). But is this simple mechanical model of upper-mantle behavior consistent with the available data?

The testing of this model formed the central theme of the conference. Sessions were organized around various topics with selected formal presentations, but much of the time was reserved for informal talks, discussions, and dialogues. Among the many questions raised were the following: What is the correspondence among the many operational definitions of the lithosphere-asthenosphere boundary which have evolved on the basis of various geodetic, seismological, petrological, and rheological phenomena? What are the variations of seismic velocities and intrinsic attenuation across this boundary? What variations of viscosity and other rheological parameters mark this transition? What are the temperature conditions at the boundary, and what is the heat transfer across the boundary? What geochemical differences or petrological contrasts characterize the uppermost mantle? What are the spatial and temporal variations in the location of the boundary? Which dynamical models of the upper

mantle best account for these data? Which rheological parameters control the behavior of these models? What future experiments are necessary to further elucidate the nature of the lithosphere-asthenosphere boundary?

Appropriately, the conference began with discussions of the isostatic recovery data and the gravity data that established the concepts of the lithosphere and asthenosphere in the first place. Cathles reviewed Bonneville, Fennoscandian, and Canadian uplift data and interpreted these in terms of viscosity models. From such data one may infer the existence of a lithosphere with a thickness generally less than or equal to 100 km, but geographically highly variable. An asthenosphere approximately 75 km thick with a viscosity of 4×10^{20} P overlying a mesosphere with a viscosity near 10^{22} P is consistent with the data, but other interpretations are possible. As Cathles pointed out, in regions responding to rapid unloading, the behavior of the peripheral bulges is diagnostic of the existence or nonexistence of channel flow in a narrow asthenosphere. Peltier presented an analysis of viscoelastic rebound in many ways analogous to modern treatments of the Earth's free oscillations and showed how the problem of inference may be set up as a formal inverse problem. Such an approach to the problem of inference is badly needed, since the degree of nonuniqueness allowed by the currently available data is large, and calculations of the resolving power of the data would be useful. Dorman and Woollard reviewed various results from the study of gravity. Dorman presented preliminary results showing that compensation is nearly complete in the vicinity of the East Pacific Rise at wave numbers greater by a factor of 10 than those typical for the continental case.

A primary emphasis of the conference was on mantle rheology, and it was exciting to hear about the rapidly accumulating data on mantle materials, specifically olivine. Goetze summarized the work of the MIT group. Generally, the deformation map for olivine published by Stocker and Ashby has been corroborated. However, a large uncertainty still exists as to the location of the transition from creep governed by dislocation climb (Weertman creep) to creep governed by grain-boundary diffusion (Coble creep). This uncertainty is of some importance since upper-mantle conditions are near this boundary, and the two processes yield grossly different apparent-viscosity laws. O'Connell and D. D. Jackson addressed the problem of partial melting in the low-velocity zone and its effects on material properties. Both agreed that the identification of the low-velocity zone with the asthenosphere is formally incorrect: incipient melting will

substantially reduce seismic velocities, but as long as the amount of melt is small, its effect on viscosity is probably negligible. Twiss and Sammis discussed two types of superplasticity that may significantly reduce the effective viscosities of mantle materials. Twiss presented some evidence to indicate that grain-boundary superplasticity may be important at mantle conditions, whereas Sammis showed that transformational superplasticity may act to "lubricate" the 400-km phase transition. Melosh presented new evidence for a non-Newtonian asthenosphere based on postseismic recovery data.

Attention was then turned to the seismic data that in many ways provide the most detailed information on the structure of the lithosphere and asthenosphere. A new development in seismology has been the construction of seismometers that can be deployed directly on the ocean floor, and long-line refraction experiments using these instruments are yielding the first good estimates of compressional velocity distributions in the oceanic upper mantle. The degree of international interest in these projects was indicated by the fact that representatives of ocean-bottom seismology groups from France, Germany, Japan, and the United States attended the conference. Orcutt discussed the Scripps ocean-bottom seismometer (OBS) profiles along the East Pacific Rise, which require the existence of a shallow (5-km) low-velocity zone beneath the axis of the rise. This zone is postulated to be the magma chamber feeding the volcanic activity along the rise. Lewis presented OBS data collected by the University of Washington in the same region; these data constrain this low-velocity zone to be a very narrow feature, since it is not evident on profiles perpendicular to the rise axis. Lewis's data also require a velocity anisotropy near the rise axis of the sort seen elsewhere in the Pacific, and he argued that the crust must thicken with age. Odegard from the University of Hawaii and Asada from Tokyo University both presented data from the older parts of the Pacific. The Hawaiian data from the North Pacific do not require the existence of a *P*-wave low-velocity channel in the upper mantle. The Japanese data from the western Pacific suggest that a fairly narrow *P*-wave low-velocity channel exists at about 90-km depth, but this feature is not as thick as, nor has it the contrast of, the shear-wave low-velocity zone inferred from surface-wave data. Therefore, the material in the shear-wave low-velocity zone is probably characterized by high values of Poisson's ratio at seismic frequencies.

Another feature of Asada's model is a transition from normal sub-Moho velocities (8.2 km/s) to high velocities (8.6 km/s) at a depth of 60 to 70 km. Such high velocities in the lower lithosphere are also indicated by French profiles in the Atlantic, presented at the conference by Steinmetz, and had been observed previously in the Gulf of Mexico. These high velocities stimulated much discussion as to their origin. Two hypotheses were offered, each with strong proponents: the high velocities may be explained either by velocity anisotropy similar to that observed at shallower depths within the mantle or else by garnet enrichment in the lower lithosphere. If the former explanation is correct, then the nature of this anisotropy could yield valuable constraints on mantle-flow models, whereas if the latter is true, the more popular models of lithospheric evolution will have to be revised. It was agreed that experiments should be conducted to discriminate between these two hypotheses.

Fuchs discussed the fine structure of the lower lithosphere from explosion seismic experiments in continental Europe. He argued that these data require a laterally inhomogeneous lithosphere and presented what he called the "peanut" model involv-

ing dispersed, thin, high-velocity regions. The idea that the lower lithosphere is as heterogeneous as the material above it was received warmly by the geologists and geochemists.

Kanamori showed that surface-wave data require that the shear-wave low-velocity zone begins at shallow depths beneath marginal basins, and he interpreted this to imply that the lithosphere in these regions is very thin—an inference consistent with their observed high heat flow.

Meyer presented some array observations made in Florida of shots fired in the Gulf of Mexico. He demonstrated how the measurement of apparent velocity can increase the resolving power in the upper mantle, and he interpreted his data in terms of a model incorporating a realistic oceanic-continental transition zone.

Continent-ocean heterogeneity on a much larger scale was the subject of several papers. Sacks used amplitude data from broadband instruments to infer the existence of a continental root characterized by low attenuation and extending to a depth of 400 km beneath western South America. Alexander summarized the geophysical data that suggest deep continental structure, including surface-wave observations and geodynamic constraints. Sipkin presented observations of lateral differences in vertical travel times through the upper mantle derived from shear waves multiply reflected from the core-mantle boundary. These data demonstrate that large-scale upper-mantle heterogeneity correlates very well with surface tectonic features. The large magnitude of the shear-wave travel-time differences between continents and oceans seems to demand that velocity differences persist to depths equal to or exceeding 400 km. These differences were interpreted by Jordan and Alexander to be an indication that the plate thickness beneath stable continental regions (shields) is on the order of 400 km. Jordan discussed thermal models of continents and showed how these thick continental roots might develop through the process of continent-continent collision.

The hypothesis of thick continental plates was certainly not received with unanimity. Crough presented an analysis of continental topography and heat flow suggesting that the continental plates thicken with time, but that maximum thicknesses are probably not greater than 200 km. Others questioned the compatibility of the thick-root hypothesis with currently accepted models of upper-mantle convection.

It was obvious to the participants of this conference that the questions regarding lateral variations in the configuration of the lithosphere-asthenosphere boundary cannot be resolved without a more complete understanding of mantle temperatures. Chapman and Pollack presented a global heat-flow model derived from existing observations supplemented in areas without data by an empirical predictor based on tectonic setting and age. They argued that the depth at which both the oceanic and continental geotherms reach approximately 0.85 of the solidus temperature is a consistent estimator of the depth to the top of the shear-wave low-velocity zone, and they used this relationship to obtain a map of lithospheric thickness. In the shield areas their estimates of thickness exceed 300 km.

Direct checks on the thermal models derived from heat-flow observations are available by several methods. One potentially powerful technique is the inference of temperatures from electrical conductivity studies. Electrical conductivity measurements in North America and Africa were presented by Gough. The difficulties with modeling complex current fields are severe, but useful conclusions about the electrical conductivity structure at asthenospheric depths have been obtained. In particular, a striking structural contrast is observed across the Rocky Mountain

front, with higher conductivities observed in the Basin and Range province, presumably reflecting higher temperatures. However, the resolving power of these data appears to be poor.

The constitutive relationships between electrical conductivity and temperature were reviewed by Shankland. Additional laboratory work will be necessary before much quantitative information about temperature, composition, and state of the mantle can be realized by electromagnetic sounding. Shankland did point out, however, that the data from the Basin and Range do seem to require the presence of partial melting. He also emphasized the necessity of controlling the oxygen fugacity in laboratory experiments.

Boettcher discussed the possibilities of inferring mantle temperatures by petrological and geochemical analyses of xenoliths recovered from magmas, emphasizing that more work is needed before the temperature and pressure estimates can be used reliably in geophysical models. Nixon summarized the kimberlite nodule data from South Africa and presented one model of mantle evolution consistent with these data. He and F. R. Boyd have used the information from these xenoliths to construct thermal and chemical profiles to depths of 200 km. Their model is characterized by an "inflected" geotherm, and they identify the kink in this geotherm with the lithosphere-asthenosphere boundary. They point out that the kink generally coincides with a change in textural and chemical properties. In particular, the rocks show an apparent increase in "fertility" (enrichment in lithophile elements) with depth, which suggests that the subcontinental lithosphere has undergone chemical differentiation (that is, the extraction of a basaltlike component). Mysen discussed the importance of the incompatible elements on the location of the solidus, and he pointed out that because the subcontinental mantle seems to be depleted, its solidus may be at higher temperatures than the oceanic solidus. This would possibly explain some of the observed differences in seismic velocities. Both he and Green emphasized the importance of CO₂ as a volatile phase in the mantle. Basu discussed a suite of diopside-rich ultramafic xenoliths from Baja California and suggested that these may be samples of the suboceanic low-velocity zone.

The ideas concerning the creation of lithosphere at spreading centers received much attention. Presnall discussed the genesis of oceanic magmas in the light of recent laboratory work and stressed that the role of volatiles in processes involving large amounts of melting is minimal. A model of the lithosphere-asthenosphere boundary near spreading centers was given by

Solomon, who synthesized a wide variety of geophysical data including his own important work on attenuation. Mantle plumes, thought by some to be a possible source of ridge material, were modeled by Yuen, who incorporated into his calculations a non-Newtonian temperature-dependent rheology.

The mechanical behavior of the lithosphere was scrutinized in papers by O. L. Anderson, Rice, and Rundle, with particular attention devoted to the deformation of the western United States.

A series of papers dealt with general models of mantle convection and lithospheric evolution. Tozer reviewed the concepts of the lithosphere and asthenosphere, emphasizing that their nature cannot be divorced from the behavior of the global convection process. D. L. Anderson reviewed the evidence critical in the formulation of a general geophysical model. Kaula discussed the thermal evolution of the Earth in the context of comparative planetology. The physics governing vertical instabilities in the low-velocity layer was presented by Ramberg.

Highlighting these discussions was the comparison by Schubert of thermomechanical models for the oceanic and continental upper mantles. In these calculations he, Froideveaux, and Yuen have used a non-Newtonian temperature-dependent rheology. He concluded that the shear zone is concentrated by thermal feedback into a relatively narrow region. He showed that shear heating may contribute significantly to the heat flow in the older parts of the ocean. In his preferred model the depth to the lithosphere-asthenosphere boundary beneath the continents is about 200 km, but this depth depends strongly on the activation volume assumed in the constitutive equation.

The conference was closed by four speakers recruited for the difficult task of summarizing and commenting on what they had seen and heard. Fyfe pointed to the increasing geochemical and geophysical evidence that the mantle is heterogeneous on many scales. He emphasized the importance of recycling via the subduction process, which ultimately must control the balance of volatiles and heat-producing elements, especially potassium. Oliver reminded the participants that many of the quandaries voiced throughout the conference would disappear with a strong dose of good observations. Goetze was optimistic: he was impressed by the consistency of many diverse data, from the laboratory and from the field, on the mechanical properties of the lithosphere and the asthenosphere. Press, with usual lucidity, placed the week's deliberations in perspective, listing the many questions raised and the few questions answered and pointing to the challenges that lie ahead.

Participants

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L. Dorman
C. L. Drake
J. Ewing
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H. W. Green
C. E. Helsley
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R. J. Twiss
G. P. Woollard
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