between washings (not shown), but was too large and too steady to be due to contamination, there is no immediate explanation.

18. Because of the 46 to 1 excess of $Na^+$ over $K^+$ in seawater, the barely perceptible percentage decrease in $Na^+$ corresponds to an actual $Na^+$ deficit several times larger than the $K^+$ deficit. This $Na^+$ must be made up mainly by $Mg^{++}$, which implies a percentage enrichment of $Mg^{++}$ perhaps half as great as the $K^+$ depletion. Since the ion exchange with the clays occurs at constant total cation normality, and since our chromatographic process cancels out the effect of any evaporation, the $Mg^{++}$ difference in milliequivalents per liter can be calculated directly as the negative sum of the $Na^+$, $Ca^{++}$, and $K^+$ differences.
19. To verify that the $K^+$ depletions and enrichments were real and not an artifact of the analysis, the seawater from the first cold washing of the 12.9 percent clay mixture and from the first warm subsequent washing were analyzed for us by Dr. Peter Brewer, using atomic absorption spectroscopy. By this technique the warm washing was found to have about 8 percent more $K^+$.
20. O. V. Shishkina, *Tr. Inst. Okeanol. Akad. Nauk SSSR* **17**, 148 (1956); English translation circulated by National Institute of Oceanography, Great Britain.

21. Supported by AEC contract AT(30-1)-3838. E.D.'s participation was supported by a summer studies grant from Swarthmore College. Publication No. 2248 from Woods Hole Oceanographic Institution.

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## The Suboceanic Mantle

Abstract. *An independent determination of density in the suboceanic lithosphere gives 3.5 to 3.6 grams per cubic centimeter at a depth of about 100 kilometers. This high value implies the existence of an ecologitic facies. A mechanism is proposed in which eclogite fractionation from the underlying, partially molten asthenosphere plays a key role in the creation and the spreading of the rigid, lithospheric plate.*

The composition, state, and mechanical properties of the crust and mantle beneath the sea floor are highly pertinent to the mechanism of sea floor spreading and continental drift and are key to understanding the origin of basic and ultrabasic rocks. In this report I give the first independent determination of the density in a portion of the suboceanic upper mantle. Previously only relative densities could be inferred from lateral variations in gravity, or very approximate indications could be obtained by using seismic velocities and empirical or theoretical equations of state. The latter results were rough

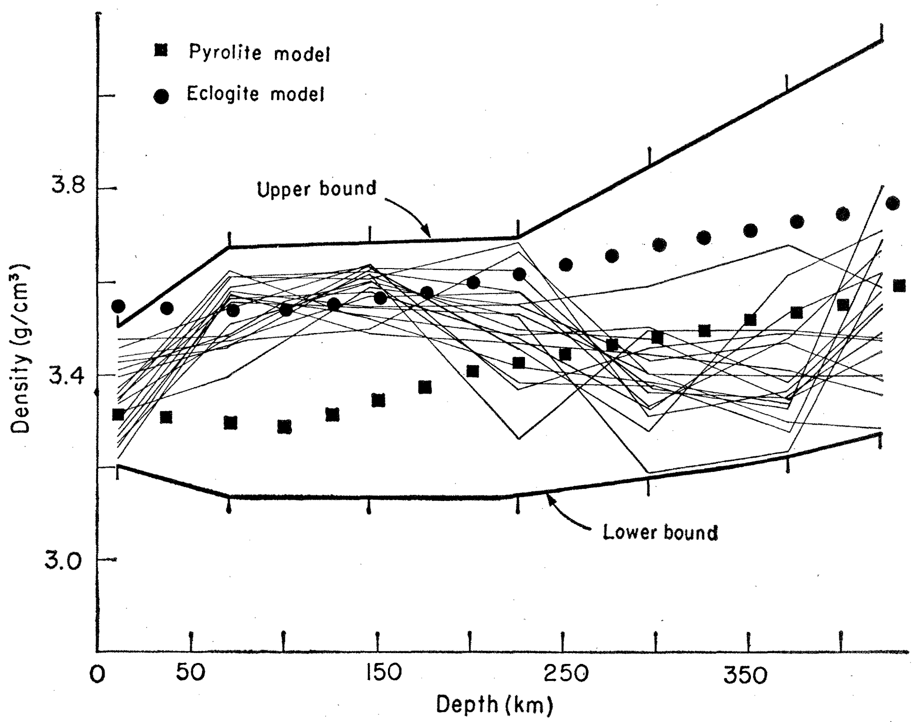


Fig. 1. Successful density models for the suboceanic upper mantle. Bounds define range permitted in Monte Carlo selection. Points show density values according to Clark and Ringwood (*10*) for pyrolite and eclogite mantles.

not only because of the uncertainty in the seismic velocity distribution below the very top of the mantle but also because of the dependency of the equation of state on composition and temperature.

The following geophysical data have been inverted to obtain density and shear velocity models representative of a section from the sea surface to the center of the earth: spheroidal oscillations of the earth ${}_0S_0$, ${}_0S_2$ through ${}_0S_{22}$, ${}_1S_2$, ${}_1S_3$, ${}_1S_5$, ${}_1S_6$, ${}_1S_8$, ${}_1S_{12}$, ${}_2S_4$, ${}_2S_6$, ${}_2S_{10}$; toroidal oscillations (*1*) ${}_0T_3$ to ${}_0T_{21}$; Rayleigh wave phase velocities (*2*) for predominantly oceanic paths, in the period range 125 to 325 seconds; Love wave phase velocity for oceanic paths (*3*), period range 80 to 340 seconds; shear velocity distribution in the lower mantle restricted to a narrow range below 800 km determined from apparent shear wave velocities at the Large Aperture Seismic Array in Montana and concomitant shear wave travel times in the range 30° to 100° (*4*); a fixed compressional wave velocity distribution (*5*); mass and moment of inertia of the earth (*6*). The uncertainty in the eigenperiod and dispersion data was taken to be ± 0.4 percent, which should allow for asphericity and experimental errors (*7*); the shear wave travel times were required to fit to within ± 5 seconds, which represents the scatter in the observations.

The surface wave data derived from oceanic paths primarily provide the resolving power for the structure of the upper mantle under the oceans. These data merge smoothly into the eigenperiod data at a long period, as would be expected if gross lateral variations do not persist below the asthenosphere. The shear wave data primarily constrain the mantle below 800 km. Although the emphasis in this report is on the upper mantle, all of the data must be used to obtain self-consistent models and absolute rather than relative values of upper-mantle density. This procedure allows us to use nearly homogeneous data where most needed, that is, in deducing the structure of the suboceanic upper mantle.

A Monte Carlo procedure was used to find earth models consistent with the preceding data. In comparison with that reported previously (*8*) the program can find a larger number of successful models from among the millions of randomly generated models. The successful models fit a more extensive suite of new data with better precision than was achievable in the earlier study. The eigenperiods, for example, typically fit the data to ± 0.2 percent, although ± 0.4 percent was acceptable.

Complete details of the successful models will be published elsewhere (*9*). Figure 1 shows density distributions to a depth of 400 km for 18 successful models. Heavy solid lines show bounds of permissible solutions, and ticks on these lines indicate depths at which density and velocity were varied randomly (linear gradients being assumed between these points). At the very top of the mantle where the models begin, the densities occupy the entire permissible range, indicating that the data are insufficient to constrain the models to narrow (and geophysically interesting) bounds. However, in the vicinity of 100 km the densities fall in the narrow band between 3.5 and 3.6 g/cm$^3$, which lies in the upper part of the permissible range. To confirm this result, biased searches were made without success to find acceptable models with densities falling below 3.4 g/cm$^3$ in this depth range. In the depth range 250 to 400 km, control of density deteriorates, with the models filling more than half the permissible range.

Also plotted in Fig. 1 are densities computed by Clark and Ringwood (*10*) for petrologic models of the mantle composed of pyrolite and eclogite. Their eclogite model alone is consistent with my results between 80 and 150 km. Either model is acceptable above this region, and the pyrolite model is weakly favored in the region near 300 km. I shall return to this result later.

The successful models differ because of errors in the data and nonuniqueness of the inversion due to lack of a complete data set. With regard to the latter, Backus and Gilbert (*11*) have provided a powerful method (δ-ness criterion) for drawing conclusions about earth structure from a given set of earth data. They showed that properly chosen data, in certain cases, can yield local values of density and velocity obtained from a single model by averaging these parameters over a restricted depth range. These local averages are stable even though details of successful models differ as in Fig. 1. In computing the averages, weighting functions are used which are determined directly from the data. If the weighting functions are concentrated over narrow depth intervals (that is, short resolving lengths) then geophysically meaningful resolution is possible. Weighting functions pertinent to my data were calculated by Wiggins (*12*). These functions together with my density models yield average densities which all fall in the range 3.5 to 3.6 g/cm$^3$ for the depth interval 75 to 125 km. The agreement to 0.1 g/cm$^3$ in the local average density for each of 27 successful models verifies numerically the stability predicted by Backus and Gilbert for weighted averages obtained according to their δ-ness criterion. Presumably the average density near 100 km is uniquely determined and any model computed from our data set should give the same value. The resolution deteriorates below 100 km. For example, at 300 km the resolving length is 200 km.

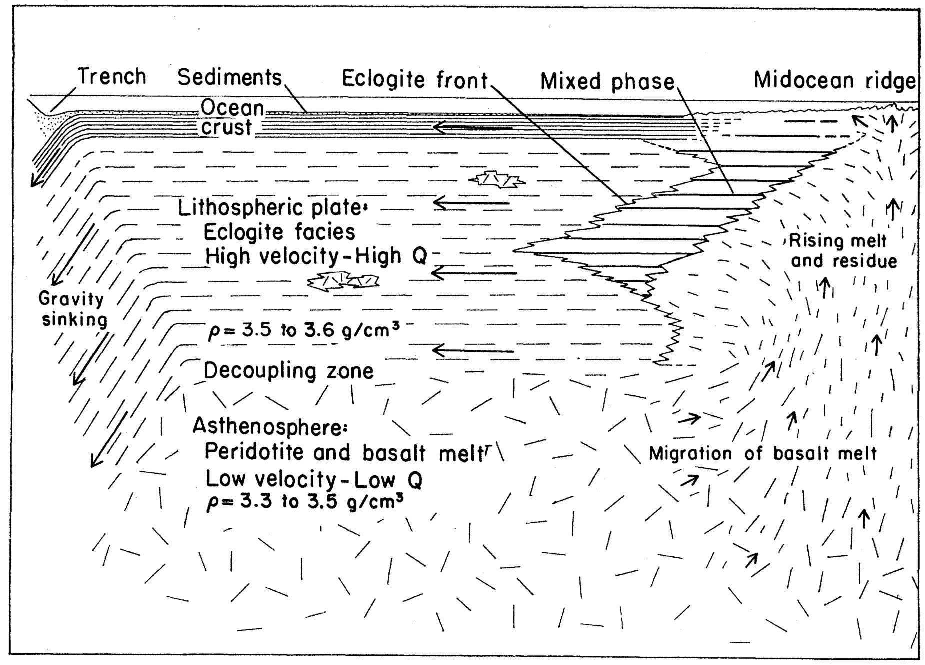


Fig. 2. Role of eclogite fractionation in the creation of the suboceanic lithospheric plate (not to scale).

All successful models show a low velocity zone for shear waves with a lid about 100 km thick. The center of the low velocity zone occurs at depths between 150 and 250 km. The low shear velocity below 150 km supports, on physical grounds, models with low densities below 150 km, implying a density reversal from 3.5 to 3.6 g/cm$^3$ at 100 km to 3.3 to 3.5 g/cm$^3$ at 300 km. No model without a low velocity zone was found, despite a special search in which only monotonic models were generated. Possibly the monotonic model reported by Haddon and Bullen (*13*) resulted from a lack of resolution in their work because only modes through $n = 44$ were used.

More complex models for the upper mantle were also found, involving two low-velocity or low-density zones. These models also indicate high density in the upper mantle.

Recent data in support of sea floor spreading and continental drift also imply that the suboceanic mantle-crust system consists of a lithosphere about 100 km thick which behaves mechanically like a rigid plate (*14*). It is underlain by the asthenosphere which is associated with the low velocity, low Q zone and presumably is a region of low strength. These properties of the asthenosphere probably result from partial melting, forming basaltic magma and peridotite or dunite residue (*15*). The lithospheric plate is produced beneath midocean ridges from which it spreads away, cooling in the process (*16*). The asthenosphere serves to decouple the plate from the underlying mantle.

My results uniquely associate high densities of 3.5 to 3.6 g/cm$^3$ with at least the lower half of the lithosphere and suggest reduced densities (3.3 to 3.5 g/cm$^3$) in the asthenosphere. The high density for the lower part of the lithosphere indicates that there it is predominantly of eclogitic composition (*17*). I propose that fractionation of eclogite is a key element in the synthesis of the lithosphere (*18*). The mechanism, depicted in Fig. 2, involves the basalt-eclogite phase transition (*19*). Basaltic melt rises buoyantly under midocean ridges together with residual dunite or peridotite which moves upward as part of a large-scale advective process involving the asthenosphere and lithosphere. The basalt is extruded to form the ridges, but large amounts are also intruded within the mantle to depths around 100 km. The material cools as it moves laterally away from the ridges, the basaltic melt cooling as a closed system. When critical temperatures are reached at various depths, a zone is defined in which the material solidifies and transforms to an eclogitic facies.

The shape and width of the transformation zone depend on the details of the isotherms in the spreading lithosphere and the nature of the boundary between the basalt and eclogite stability field. The former depends on the spreading rate and the lithosphere thickness (*16*) and the latter on the composition of the melt (*19*). With so many parameters to adjust, only general statements can be made. The transformation front can be complex in shape and may extend laterally 1000 km or more from the ridge, for the higher spreading rates. An extensive intermediate mixed phase region may occur, analogous to the pyroxene and garnet granulite facies discussed by Ringwood and Green (*19*). Below about 70 km the melt would transform directly to eclogite.

A minimum thickness of about 35 km of eclogite is indicated by assuming that the eclogite facies has a density 3.5 g/cm$^3$, is 70 km thick, and contains 50 percent eclogite. The melting of large amounts of basalt is implied by the proposed mechanism. Conceivably this could be derived from an asthenosphere (without fully depleting it) about 300 km thick if the level of partial melting is about 15 percent. Otherwise, a source in the deeper mantle would be needed. Inasmuch as our results do not specify the density at the very top of the mantle, the suboceanic M-discontinuity could represent a composition or phase change or hydrous metamorphism.

The dense lithosphere overlying a less dense asthenosphere is gravitationally unstable. Gravitational sliding, which has been suggested as the driving mechanism for the spreading sea floor, would be enhanced by the density inversion (*20*).

The proposed mechanism is similar in some respects to several earlier concepts. A shell of eclogite around the earth was proposed by Birch, by Lovering, and by Kennedy, among others (see *21*). Birch argued, as I do, that the conventional density of 3.3 g/cm$^3$ for the top of the mantle was too poorly founded to eliminate eclogite from consideration on this basis. Ringwood and Green (*19*) proposed that the transformation of small pockets of basalt to eclogite in the crustal segment of the lithospheric plate drags the crust down near continental margins or island arcs or both. They did not envisage the large-scale transformation to eclogite proposed here. Talwani *et al.* (*22*) used gravity profiles together with seismic refraction data to infer the existence of a wedge of low-density "anomalous mantle" below the normal mantle and extending as far as 1000 km from the mid-Atlantic ridge and even farther from the east Pacific rise. They suggested that the anomalous mantle was transformed from normal mantle by an unspecified phase change. Simple changes in density and the shape of their anomalous mantle can reconcile their hypothesis with mine and relate their proposed phase change to the basalt-eclogite transformation. The fit to the gravity and seismic refraction data remains unaltered. I take this as substantial support for my concept of the role of eclogite fractionation in the origin of the suboceanic lithosphere.

The preceding conclusion requires the use of all of the experimental data cited earlier, but rests particularly on the phase velocity of surface waves for oceanic paths. Numerical tests indicate that an accuracy of 1 percent in these data is required to establish the high density for the lithosphere. An error analysis of the experiment indicates that this precision was achieved for Love and Rayleigh waves. Comparison with phase velocities for other oceanic paths verifies this (*23*). One source of uncertainty is the reduction of suboceanic surface wave phase velocities due to the effect of dissipation or to passage across midocean rises (see *24*). However, correction for these factors would tend to raise the densities to slightly higher values than I found.

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**References and Notes**

1. I have used the experimental eigenperiods as reviewed and summarized by J. S. Derr (*Bull. Seismol. Soc. Amer.*, in press) except as follows: $_0S_2$, 3229.0 seconds; $_0S_{11}$, 537.5 seconds.
2. A. Ben-Menahem, *J. Geophys. Res.* **70**, 4641 (1965).
3. M. N. Toksöz and D. L. Anderson, *Trans. Amer. Geophys. Union* **46**, 157 (1965).
4. J. Fairborn, thesis, Massachusetts Institute of Technology (1968).
5. The fixed compressional velocity in the mantle is very close to the array-determined models of L. R. Johnson (personal communication) and J. Fairborn (*4*). Numerical tests show that use of a variable compressional velocity would not alter the conclusions regarding density. The velocity in the core is fixed and based on the results of E. S. Husebye and M. N. Toksöz (*J. Geophys. Res.*, in press).
6. I have used $5.976 \times 10^{27}$ g and 0.3308 for the mass and dimensionless moment of inertia of the earth.
7. Errors due to asphericity were recently discussed by F. A. Dahlen, *Geophys. J.* **16**, 329 (1968).
8. F. Press, *J. Geophys. Res.* **73**, 5223 (1968).
9. ———, *Phys. Earth Planet. Int.*, in press.
10. S. P. Clark, Jr., and A. E. Ringwood, *Rev. Geophys.* **2**, 35 (1964).
11. G. Backus and F. Gilbert, *Geophys. J.* **16**, 169 (1968).
12. These weighting functions extend the numerical work of Backus and Gilbert (*11*) in considering velocity and density. I am grateful to Dr. Ralph Wiggins for allowing me to use his results in advance of publication.
13. R. A. W. Haddon and K. E. Bullen, *Phys. Earth Planet. Int.* **2**, 35 (1969).
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15. See, for example, H. S. Yoder and C. E. Tilley, *J. Petrol.* **3**, 342 (1962); D. H. Green and A. E. Ringwood, *Contrib. Min. Petrol.* **15**, 103 (1967); A. P. Vinogradov, *Geochemistry USSR, English Transl.* **1961**, 1 (1961).
16. Isotherms for a spreading lithosphere have been computed under various assumptions by N. H. Sleep, *J. Geophys Res.* **74**, 542 (1969); M. G. Langseth, X. LePichon, M. Ewing, *ibid.* **71**, 5321 (1966); D. P. McKenzie, *ibid.* **72**, 6261 (1967).
17. The association of high density with eclogite is not unique and is only justified if the choice is made from the current (petrologic) hypotheses for the composition of the upper mantle.
18. The fractionation of eclogite from a more primitive rock (for example garnet peridotite) has been discussed by several investigators, for example: Yoder and Tilley (*15*); M. J. O'Hara, *Earth Sci. Rev.* **4**, 69 (1968); ——— and H. S. Yoder, *Scot. J. Geol.* **3**, 67 (1967).
19. For a review, see A. E. Ringwood and D. H. Green, *Tectonophysics* **3**, 383 (1966).
20. A. Hales, *Program, Annual Meeting Geological Society of America* (1968), p. 124.
21. F. Birch, *J. Geophys. Res.* **57**, 227 (1957); G. C. Kennedy, *Amer. Scientist* **47**, 491 (1959).
22. M. Talwani, X. LePichon, M. Ewing, *J. Geophys. Res.* **70**, 341 (1965).
23. For example, comparison of phase velocities in Love and Rayleigh waves of Ben-Menahem (*2*) and A. Dziewonski and M. Landisman (personal communication) for entirely different (mostly oceanic) paths, sources, and procedures reveals agreement to 0.5 to 0.7 percent. This argues against the possibility that systematic or other errors in data could vitiate my conclusions.
24. D. Davies, *Geophys. J.* **13**, 421 (1967). Davies overestimates the effect of dissipation by a factor of about two, since I use 15-second shear waves rather than the 1-second shear waves of his calculation.
25. The technique was developed as part of an inversion procedure for lunar geophysical data with support from NASA under grant NGR 22-009-123. The application to the earth was supported by the Air Force Office of Scientific Research under contract AF 49 (638)-1632. Joel Karnofsky was an invaluable assistant in this study.

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