NIKOLAS I. CHRISTENSEN *Department of Geological Sciences, University of Washington, Seattle, Washington 98105*

Possible Greenschist Facies Metamorphism of the Oceanic Crust

ABSTRACT

Compressional wave velocities are reported to pressures of 6 kb for 15 cores of greenstone. The experimental velocities for greenstone are shown to be similar to velocities obtained from seismic refraction measurements of layer 3 of the oceanic crust, thus suggesting that greenschist facies metamorphism may be important in lower oceanic crustal rocks.

INTRODUCTION

The hypothesis of sea-floor spreading has recently had a substantial impact on the fields of geology, oceanography, and geophysics. Ocean ridges are believed to be areas of oceanic crustal generation (Hess, 1962). Several lines of evidence suggest that volcanic processes play an important part in the formation of oceanic crust. Dredging operations have found basalt to be abundant near oceanic ridge crests (*see*, for example, Quon and Ehlers, 1963; Engel and others, 1965; van Andel and Bowin, 1968). The concentrations of earthquake swarms along the crestal zones of ridge systems also suggest that submarine volcanic eruptions are presently adding new material to the oceanic crust (Isacks and others, 1968).

Dredge hauls in the vicinity of the median valley of the Mid-Atlantic Ridge have also recovered numerous low-grade metamorphic derivatives of basalts (Melson and van Andel, 1966; Melson and others, 1968; Aumento and Loncarevic, 1969). Many of the dredged metabasalts have undergone complete mineral reconstitution to various combinations of albite, chlorite, epidote, actinolite, pumpellyite, quartz, and saponite, which are characteristic greenschist-facies assemblages. As these rocks were recovered along the rift valley of the ridge, where first motion studies of seismic waves from earthquakes show a predominance of normal faulting (Isacks and others, 1968), the possibility exists that the greenstones represent portions of the deeper oceanic crust now exposed due to faulting along the median valley walls. This is supported by an increase in metamorphic grade with depth of recovery of the greenstones (Melson and van Andel, 1966). An alternate interpretation is that the metamorphism was produced at relatively shallow levels by hot solutions derived from deeper-seated intrusions (Melson and others, 1968).

COMPRESSIONAL WAVE VELOCITIES IN GREENSTONES

Seismic velocities are one of the few properties measurable at depth within the earth. These velocities, along with related elastic properties calculated from the velocities, have often been correlated with laboratory measurements of ultrasonic velocities in rocks, with the objective of arriving at reasonable estimates of the composition of the earth's interior. Compressional wave velocities of the lower oceanic crust are well known in many localities (Raitt, 1963), however, little attention has been given to laboratory measurements of the elastic properties of greenstones at lower crustal pressures. In order to evaluate the possibility of greenschist facies metamorphism in the lower oceanic crust, velocities have been measured to pressures of 6 kb for several different greenstones. The compressional wave velocities, bulk densities, and mineral assemblages of the greenstones are given in Table 1.

The samples of metabasalt and epidosite from Luray, Virginia, are described in detail by Reed (1955). Chemical analyses of these two rocks are given in Table 2. A chemical analysis and description of the Black Mountain greenstone from Marin County, California, are reported by Bailey and others (1964, p. 49). Davis (1966) has described the greenstones

Geological Society of America Bulletin, v. 81, p. 905–908, 1 fig., March 1970

TABLE 1. COMPRESSIONAL WAVE VELOCITIES IN GREENSTONES (KM/SEC)

Sample	Density (g/cc)	Pressure (kb)						
		0.1	0.4	0.7	1.0	2.0	4.0	6.0
Metabasalt 1*	2.88	6.7	6.74	6.76	6.78	6.82	6.86	6.89
Yreka, Calif.	2.90	6.7	6.80	6.82	6.85	6.89	6.93	6.97
	2.94	6.7	6.83	6.86	6.90	6.99	7.08	7.12
Mean	2.91	6.7	6.79	6.81	6.84	6.90	6.96	6.99
Metabasalt 2†	2.92	6.5	6.54	6.58	6.61	6.69	6.75	6.78
Luray, Va.	2.94	6.5	6.54	6.58	6.60	6.66	6.72	6.77
	2.93	6.4	6.47	6.51	6.54	6.60	6.66	6.71
Mean	2.93	6.5	6.52	6.56	6.58	6.65	6.71	6.75
Metabasalt 3‡	2.93	6.6	6.70	6.73	6.76	6.80	6.86	6.91
Mt. Vernon, Wash.	2.93	6.6	6.71	6.74	6.76	6.81	6.87	6.92
	2.95	7.1	7.12	7.14	7.16	7.20	7.26	7.30
Mean	2.94	6.8	6.84	6.87	6.89	6.94	7.00	7.04
Epidosite§	3.17	5.9	6.19	6.49	6.72	7.04	7.18	7.24
Luray, Va.	3.17	6.1	6.40	6.67	6.78	7.03	7.15	7.22
	3.16	6.2	6.40	6.69	6.80	7.01	7.15	7.23
Mean	3.17	6.1	6.33	6.62	6.77	7.03	7.16	7.23
Metadiabase#	2.86	5.9	5.98	6.16	6.22	6.35	6.50	6.61
Marin County,	2.87	5.9	6.21	6.38	6.45	6.53	6.65	6.75
Calif.	2.91	5.9	6.22	6.32	6.38	6.51	6.63	6.73
Mean	2.88	5.9	6.14	6.29	6.35	6.46	6.59	6.70

* plagioclase, actinolite, clinozoisite, chlorite, quartz
† albite, epidote, chlorite, actinolite, magnetite
‡ albite, pumpellyite, chlorite, prehnite (?)
§ epidote, quartz, albite, actinolite
# plagioclase, pumpellyite, chlorite, pyroxene, magnetite

from the vicinity of Yreka, California. The greenstone from Mt. Vernon, Washington, is part of the Shuksan metamorphics described by Misch (1966).

The technique for measuring the velocities was similar to earlier descriptions (Birch, 1960; Christensen, 1965). Velocities were measured from each sample in three mutually perpendicular directions from cores 2.6 cm in diameter and 6 to 7 cm long. Pressure was generated by the use of an intensifier connected to a cylindrical pressure vessel with an outside diameter of 28 cm and an inside diameter of 4.5 cm.

TABLE 2. CHEMICAL ANALYSES OF GREENSTONES FROM LURAY, VIRGINIA

Specimen	Metabasalt	Epidosite
SiO_2	48.79	51.56
Al_2O_3	13.91	13.19
TiO_2	2.26	2.14
Fe_2O_3	5.13	10.45
FeO	8.40	2.27
MnO	0.25	0.16
MgO	6.67	2.16
CaO	7.36	15.46
Na_2O	3.23	0.13
K_2O	0.07	0.01
P_2O_5	0.24	0.21
H_2O^+	3.43	1.81
H_2O^-	0.06	0.06
CO_2	0.07	0.01
Total	99.87	99.62

DISCUSSION

The greenstone velocities at pressures comparable to lower oceanic crustal pressures are shown in Figure 1 along with 121 velocities tabulated by Raitt (1963) from seismic refraction measurements. All laboratory measurements were made at temperatures between 20° and 30° C. The effect of higher temperatures would produce a slight lowering of the velocities.

The results of these new measurements on greenstones reinforce the possibility that the lower oceanic crust is composed of metamorphosed basalt as suggested by Oxburgh (1967), Cann (1968), and Oxburgh and Turcotte (1968). It is emphasized, however that compressional wave velocities do not yield unique information on composition. Other probable lower oceanic crustal rocks which appear to have acceptable compressional wave velocities are amphibolite, gabbro, and par-

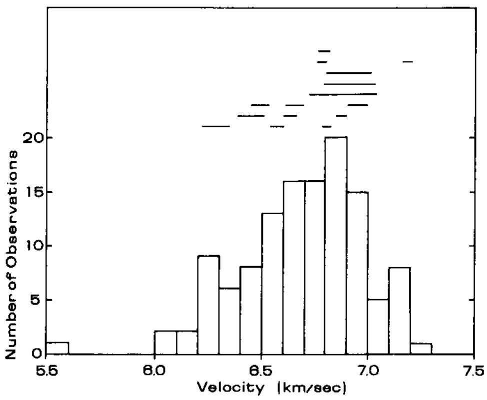

Figure 1. Compressional wave velocities in the lower oceanic crust (Raitt, 1963). Horizontal bars represent greenstone velocities at pressures between 1 and 2 kb.

tially serpentinized peridotite (Birch, 1960; Christensen, 1965, 1966). Since lower crustal velocities obtained seismically usually represent propagation paths of several kilometers, it seems unlikely that the reported velocities are averages for homogeneous material. It may be found that the lower oceanic crust is composed of rocks of several mineral assemblages among which greenstones are important constituents.

ACKNOWLEDGMENTS

The research for this paper was supported by National Science Foundation grant GA-1461. I thank K. V. Campbell, P. Lage, M. Mulcahey, and G. Shaw for technical assistance. T. Simkin collected the greenstones from Virginia, and J. C. Reed, Jr., provided the chemical analyses presented in Table 2.

REFERENCES CITED

Aumento, F., and Loncarevic, B. D., 1969, The Mid-Atlantic Ridge near 45° N. III. Bald Mountain: Canadian Jour. Earth Sci., v. 6, p. 11–23.

Bailey, E. H., Irwin, W. P., and Jones, D. L., 1964, Franciscan and related rocks and their significance in the geology of western California: California Div. Mines Bull. 183, 177 p.

Birch, F., 1960, The velocity of compressional waves in rocks to 10 kbar, 1: Jour. Geophys. Research, v. 65, p. 1083–1102.

Cann, J. R., 1968, Geological processes at mid-ocean ridge crests: Royal Astron. Soc. Geophys. Jour., v. 15, p. 331–341.

Christensen, N. I., 1965, Compressional wave velocities in metamorphic rocks at pressures to 10 kilobars: Jour. Geophys. Research, v. 70, p. 6147–6164.

—— 1966, Elasticity of ultrabasic rocks: Jour. Geophys. Research, v. 71, p. 5921–5931.

Davis, G. A., 1966, Metamorphic and granitic history of the Klamath Mountains, p. 39–50, *in* Bailey, E. H., *Editor*, Geology of Northern California: California Div. Mines Bull. 190, 508 p.

Engel, A.E.J., Engel, C. G., and Havens, R. G., 1965, Chemical characteristics of oceanic basalts and the upper mantle: Geol. Soc. America Bull., v. 76, p. 719–734.

Hess, H. H., 1962, History of the ocean basins, p. 599–620, *in* Engel, A.E.J., James, H. L., and Leonard, R. F., *Editors*, Petrologic Studies, Buddington Vol.: Boulder, Colorado, Geol. Soc. America, 660 p.

Isacks, B., Oliver, J., and Sykes, L. R., 1968, Seismology and the new global tectonics: Jour. Geophys. Research, v. 73, p. 5855–5899.

Melson, W. G., and van Andel, Tj. H., 1966, Metamorphism in the Mid-Atlantic Ridge, 22° N. latitude: Marine Geology, v. 4, p. 165–186.

Melson, W. G., Thompson, G., and van Andel, Tj. H., 1968, Volcanism and metamorphism in the Mid-Atlantic Ridge, 22° N. latitude: Jour. Geophys. Research, v. 73, p. 5925–5941.

Misch, P., 1966, Tectonic evolution of the Northern Cascades of Washington State—a West-Cordilleran case history, p. 101–148, *in* Gunning, H. C., *Editor*, A symp. on the tectonic history and mineral deposits of the Western Cordillera in British Columbia and neighboring parts of the United States: Canada Inst. Min. Met. Spec., v. 8.

Oxburgh, E. R., 1967, Mantle convection and the thermal requirements of various crustal phenomena: Royal Astron. Soc. Geophys. Jour., v. 14, p. 403–411.

Oxburgh, E. R., and Turcotte, D. L., 1968, Mid-ocean ridges and geotherm distribution during mantle convection: Jour. Geophys. Research, v. 73, p. 2643–2661.

Quon, S. H., and Ehlers, E. G., 1963, Rocks of the northern part of the Mid-Atlantic Ridge: Geol. Soc. America Bull., v. 74, p. 1–7.

Raitt, R. W., 1963, The crustal rocks, p. 685–698, *in* Hill, M. N., *Editor*, The Sea, v. 3: New York, John Wiley and Sons, 963 p.

Reed, J. C., 1955, Catoctin formation near Luray, Virginia: Geol. Soc. America Bull., v. 66, p. 871–896.

van Andel, Tj. H., and Bowin, C. O., 1968, The Mid-Atlantic Ridge between 22° and 23° north latitude and the tectonics of mid-ocean rises: Jour. Geophys. Research, v. 73, p. 1279–1298.

MANUSCRIPT RECEIVED BY THE SOCIETY SEPTEMBER 8, 1969