Tectonophysics, 173 (1990) 207–210
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Extended abstract

Measured and calculated elastic wave velocities for xenoliths from the lower crust and upper mantle

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(Received April 20, 1989; accepted May 30, 1989)

Abstract

Jackson, I., Rudnick, R.L., O'Reilly, S.Y. and Bezant, C., 1990. Measured and calculated elastic wave velocities for xenoliths from the lower crust and upper mantle. In: J.H. Leven, D.M. Finlayson, C. Wright, J.C. Dooley and B.L.N. Kennett (Editors), Seismic Probing of Continents and their Margins. *Tectonophysics*, 173: 207–210.

Compressional wave velocities have been measured by ultrasonic pulse transmission as functions of pressure (generally to 1 GPa) on jacketed specimens prepared from a variety of mafic and ultramafic xenoliths derived from the lower crust and upper mantle beneath eastern Australia. Three broadly representative suites have been studied: (1) mafic, pyroxene-rich, garnet granulites and eclogites from the Calcutteroo kimberlite pipe in South Australia (Jackson and Arculus, 1984), (2) mafic, plagioclase-rich garnet granulites from the Chudleigh volcanic province of north Queensland (Rudnick and Jackson, in prep.), and (3) ultramafic rocks (spinel lherzolites and a garnet pyroxenite) from the adjacent Bullenmerri and Gnotuk maars and from Mt. Porndon in Victoria (O'Reilly et al., in prep.). The measured velocities typically increase sharply with increasing pressure below ~ 400 MPa as a result of crack closure, but become much less pressure sensitive at higher pressures. Specimens prepared from pervasively cracked ultramafic xenoliths (as surface-epoxy-impregnated rectangular prisms rather than the usual cylindrical cores) continue to increase substantially in velocity to 800 or even 1000 MPa (1 GPa). In either case, the velocity measured at the highest pressure (typically 1 GPa) is considered to be approximately representative of the intrinsic properties of the uncracked rock.

The fidelity with which the mean velocities measured at high pressure (averaged over three mutually orthogonal propagation directions) reflect the primary mineralogy has been assessed by comparison of the measured velocities with those calculated for the modal mineralogy from appropriate single-crystal elasticity data. The strategy outlined in Table 1 has been employed in the calculation of density and both compressional and shear-wave velocities for composites of the minerals quartz, plagioclase, clinopyroxene, orthopyroxene, olivine, spinel and garnet. The relevant elasticity data for the mineral end members are assembled in Table 2. There exists an encouraging degree of overall consistency between calculated and measured wave velocities for the freshest xenoliths. Any discrepancies are therefore diagnostic of departures of the actual mineralogy of the measured specimen from the nominal modal mineralogy often determined on a separate sample of the same xenolith. Such departures may be

0040-1951/90/$03.50

TABLE 1

The strategy for the computation of elastic wave velocities

(1) *Mineral end-members*: the effective bulk and shear moduli for isotropic polycrystals are orientational averages (HS, VRH) of single-crystal elastic moduli C_{ij}
(2) *Solid solutions*: the elastic properties of solid solutions are approximated by molar averages of end-member densities and bulk and shear moduli
(3) *Rocks*: the rocks of interest are treated as composites (HS) of isotropic mineral "phases"

For a review of the Hashin-Shtrikman (HS) and Voigt-Reuss-Hill (VRH) descriptions of the elastic properties of single-phase polycrystals and multiphase composites, see Watt et al. (1976).

TABLE 2

Elastic properties of key mineral end members represented in lower crustal/upper mantle lithologies

Mineral		Density (Mg m^{-3})	Bulk modulus (GPa)	Shear modulus (GPa)	Source [a]
Quartz		2.648	37.7	44.4	1
Plagioclase	An	2.762	89.7	40.1	2, 3
	Ab	2.617	62.0	36.4	2, 3
Ortho-pyroxene	En	3.198	107.8	75.7	4
	Fs	4.003	88.0	71.7	5
Clino-pyroxene	Di	3.280	112.9	67.1	6
	Hd	3.657	120.0	61.0	7
Olivine	Fo	3.214	128.8	81.4	8, 9
	Fa	4.393	127.9	50.3	10
Spinel	Sp	3.582	197.4	108.4	11
	Hc	4.258	210.3	84.0	12
Garnet	Py	3.559	175.0	90.0	
	Al	4.318	176.0	98.0	
	Gr	3.595	169.0	104.0	13

[a] 1 = McSkimin et al. (1965); 2 = Birch (1961); 3 = Simmons (1964); 4 = Weidner et al. (1978); 5 = These values of bulk and shear modulus preferred over those of Bass and Weidner (1984) for ferrosilite on the basis of superior fit of molar average to the properties of bronzites (Kumazawa, 1969; Frisillo and Barsch, 1972; Webb et al., 1989); 6 = Levien et al. (1979); 7 = Kandelin and Weidner (1988a); 8 = Graham and Barsch (1969); 9 = Kumazawa and Anderson (1969); 10 = Graham et al. (1989); 11 = Chang and Barsch (1973); 12 = Wang and Simmons (1972); 13 = Leitner et al. (1980)—solution 1A.

TABLE 3

Mafic granulites/eclogite xenolith suites from two Australian localities

Locality:	Chudleigh (N. Qld.)	Calcutteroo (S.A.)
Host:	Alkali basalt	Kimberlite
Chemistry		
SiO_2	49.5–51.0	48.0–51.0
Al_2O_3	18.0–20.5	12.5–15.5
MgO + FeO	16.6–18.3	17.8–23.3
CaO	8.5–10.5	10.5–16.0
Na_2O	2.5– 3.0	1.0– 2.5
Mg#	67 –80	51 –73
CIPW norm		
Feldspar	60–66	36–51
Px + Ol	23–39	41–57
Mineralogy	Plag(60 → 24%) Px (18 → 42%) ± kelyphite (< 46%) ± Ol	Cpx (30–75%) Gt (10–40%) ± Plag(< 30%) ± Qz
Equilibration conditions		
Pressure	0.5–1.3 GPa	0.8–1.2 GPa
Temperature	1000 → 700°C (isobaric cooling)	800–900°C

caused by mineralogical heterogeneity and by the neglect of porosity or low-velocity secondary phases associated with low-temperature alteration.

For the Calcutteroo suite of relatively fresh garnet granulites and eclogites (Table 3), the measured (400 MPa) compressional wave velocities range from 7.5 to 8.0 km s^{-1} (Fig. 1). The lower end of this range corresponds to calculated velocities at ambient conditions for assemblages of clinopyroxene and garnet with 25–30% quartz + plagioclase, whereas the upper end is identified with calculated velocities for plagioclase-free assemblages (eclogites). For three of the six rocks, the measured and calculated velocities are consistent within 1%; elsewhere the measured velocities are either low (alteration?) or high (mineralogical heterogeneity?) by as much as 0.5 km s^{-1}. For the more aluminous granulites of the Chudleigh suite (Table 3), in which garnet, where originally present, has been completely transformed during decompression to kelyphite (a fine-grained mixture of anorthite, orthopyroxene,

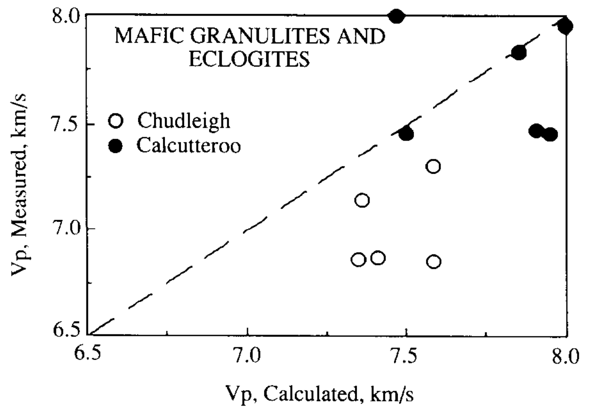

Fig. 1. Compressional wave velocities, measured at 1 GPa, and calculated from the modal mineralogy, for the mafic granulites and eclogites from two Australian xenolith suites.

clinopyroxene and spinel), the measured velocities are consistently lower than those calculated for the (decompressed) modal mineralogy (Fig. 1). For the kelyphite-bearing representatives, even higher calculated velocities are inferred for the primary garnet-bearing assemblages. These latter calculated velocities (under ambient conditions) for this essentially isochemical suite increase with increasing metamorphic grade from ~ 7.4 km s^{-1} for an olivine-bearing plagioclase-rich representative (60% plagioclase) to ~ 8.0 km s^{-1} for the most garnet-rich (45%) member of the suite.

For the ultramafic suite, measured (1 GPa) velocities for the two olivine-rich (~ 67%) spinel lherzolites and the olivine-poor spinel lherzolite (37% olivine) are within 1% of the values of 8.25–8.28 km s^{-1} and 8.10 km s^{-1}, respectively, calculated from single-crystal elasticity data. On the other hand, the measured compressional wave velocity for a partially kelyphitised garnet clinopyroxenite (50% garnet) is lower than calculated by 4%. The very low measured (relative to calculated) velocities for all xenoliths containing kelyphitised garnet might be indicative of the presence of porosity (equant micro-pores rather than cracks) introduced at the time of kelyphite formation; similar effects might be associated with the alteration of other high-density minerals (such as olivine). The measured and calculated velocities for the spinel lherzolites provide a measure of the sensitivity of V_p to the variation of the relative proportions of olivine and pyroxenes in ultramafic rocks. A decrease of 0.09 km s^{-1} for a 20% reduction in modal olivine is indicated. Calculated velocities for a typical garnet pyroxenite (80% clinopyroxene, 20% garnet) and for a garnet lherzolite (60% olivine, 20% orthopyroxene, 20% garnet) are, respectively, 8.04 km s^{-1} and 8.35 km s^{-1}. All of these calculated velocities pertain to conditions of one atmosphere pressure and 25°C, and must be adjusted for the higher temperatures and pressures prevailing in situ. The necessary pressure and temperature derivatives are fortunately not strongly dependent upon composition or mineralogy: $\partial V_p/\partial P \sim 0.1$ km s^{-1} GPa^{-1} and $\partial V_p/\partial T \sim -5 \times 10^{-4}$ km s^{-1} K^{-1} being repre-

TABLE 4

Calculated velocities along the O'Reilly-Griffin geotherm for spinel lherzolite (70% Ol) and other ultramafic and mafic lithologies

Depth (km)	Pressure (GPa)	Temperature (°C)	V_p (km s^{-1})		
–	0	25	8.23		
25	0.75	800	7.92		
30	0.90	850	7.91		
35	1.05	900	7.90		7.0–7.6 mafic granulite/eclogite
40	1.20	950	7.89		7.7 garnet pyroxenite
45	1.35	1000	7.88	~ 7.9 cf.	7.7 olivine-poor spinel lherzolite
50	1.50	1050	7.87		8.0 garnet lherzolite
55	1.65	1090	7.86		
60	1.83	1120	7.86		
65	2.00	1140	7.87		
70	2.18	1160	7.88		

sentative for a wide range of lithologies (e.g., Jackson, 1990).

The covariation of temperature and pressure along the palaeogeotherm of O'Reilly and Griffin (1985) for southeastern Australia is such that the calculated velocity for any given assemblage is essentially independent of depth between 30 km (850°C) and 70 km (1160°C)—and approximately 0.35 km s^{-1} lower than the corresponding 1 atmosphere, 25°C datum (Table 4). This geotherm has contemporary relevance only for regions of widespread recent volcanism and high present-day heat flow. Elsewhere, where sufficient time may have elapsed since the cessation of volcanic activity for lower temperatures to prevail, velocities will be higher (by ~ 0.05 km s^{-1} per 100°C).

Comparison of such calculated velocity–depth models with those of seismological origin for eastern Australia provides some firmer constraints on the lithological character of the lower crust and uppermost mantle (O'Reilly et al., in prep.; Rudnick and Jackson, in prep.).

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