

of the Birch equation of state. Thus equation 8 may be used to extrapolate to moderately high pressure. Equation 18 should be used to extrapolate to high pressure.

TEMPERATURE CORRECTION

Comparison of the seismically observed values of ϕ_{FLD} for the earth with laboratory data must be done at the same reference temperature. Consider a material suspected to occur at a depth where the temperature is T and the pressure P . The values of K_0 , V_0 , and ρ_0 determined in the laboratory at temperature t (likely room temperature) and zero pressure must be extrapolated to T and P . Either equation 8 or equation 18, as appropriate for the pressure, both of which are expressed here as the adiabatic equations of state, may be used. The generalization of these equations to an arbitrary temperature T follows a formalism presented by Gilvarry [1957, 1962] and involves replacing K_0 , V_0 , and ρ_0 (the laboratory temperature measurements) by $k(T)$, $v(T)$, and $\rho(T)$ defined as

$$\begin{aligned} k(T) &= K_0 \exp \left[- \int_t^T \psi_0 \alpha_0 dT \right] \\ v(T) &= V_0 \exp \left[\int_t^T \alpha_0 dT \right] \\ \rho(T) &= \rho_0 \exp \left[- \int_t^T \alpha_0 dT \right] \end{aligned} \quad (19)$$

where α_0 is the coefficient of volume expansion evaluated at $P = 0$ and ψ_0 is an anharmonic parameter arising from temperature effects given by

$$\psi_0 = \psi_T = -\frac{1}{\alpha} \left(\frac{\partial \ln K}{\partial T} \right)_P \quad (20)$$

At high temperature, where the specific heat at constant volume approaches the Dulong-Petit limit,

$$\psi_T = \psi_s + \gamma_G \quad (21)$$

where γ_G is Grüneisen's ratio and

$$\psi_s = -1/\alpha (\partial \ln K_s / \partial T)_P \quad (22)$$

as given originally by Grüneisen [1912, p. 278].

With this temperature correction, the tables in the appendix are still applicable if we understand the pressures to be $P/k(T)$, the relative volumes to be $[V/v(T)]_s$, and the normalized

seismic parameter to be $[\phi(P, T)/\phi(T)]_s$ where $\phi(T) \equiv k(T)/\rho(T)$.

APPENDIX

Comparison of volume and the seismic parameter ϕ as a function of pressure for different values of m . For most solids, value of m ranges from 4 to 6; Tables 1, 2, and 3 below are useful for estimating the seismic parameter (as well as volume) whenever K_0 and m are known for a solid under discussion.

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REFERENCES

- Al'tshuler, L. V., R. F. Trunin, and G. V. Simakov, Shock-wave compression on periclase and quartz and the composition of the earth's lower mantle, *Izv. Acad. Sci., USSR, Phys. Solid Earth*, Engl. transl., 10, 657, 1965.
- Anderson, D. L., and H. Kanamori, Shock-wave equations of state for rocks and minerals, *J. Geophys. Res.*, 73, 6477, 1968.
- Anderson, O. L., Two methods for estimating compression and sound velocity at very high pressures, *Proc. Nat. Acad. Sci. U.S.*, 54, 667, 1965.
- Anderson, O. L., Seismic parameter ϕ : Computation at very high pressure from laboratory data, *Bull. Seismol. Soc. Amer.*, 56, 725, 1966.
- Anderson, O. L., On the use of ultrasonic and shock-wave data to estimate compressions at extremely high pressures, *Phys. Earth Planet. Interiors*, 1, 169, 1968.
- Anderson, O. L., E. Schreiber, R. C. Liebermann, and N. Soga, Some elastic constant data on minerals relevant to geophysics, *Rev. Geophys.*, 6, 491, 1968.
- Birch, F., The variation of seismic velocities within a simplified earth model in accordance with the theory of finite strain, *Bull. Seismol. Soc. Amer.*, 29, 463, 1939.
- Birch, F., Finite elastic strain of cubic crystals, *Phys. Rev.*, 71, 809, 1947.
- Birch, F., Elasticity and constitution of the earth's interior, *J. Geophys. Res.*, 57, 227, 1952.
- Bridgman, P. W., *The Physics of High Pressure*, 445 pp., G. Bell, London, 1949.
- Bridgman, P. W., *The Collected Works of P. W. Bridgman*, vol. 1-7, Harvard University Press, Cambridge, Mass., 1964.
- Bullen, K. E., *An Introduction to the Theory of Seismology*, p. 220, Cambridge University Press, London, 1947.

- Bullen, K. E., Compressibility-pressure hypothesis and the earth's interior, *Mon. Notic. Roy. Astron. Soc.*, **5**, 355, 1949.
- Chang, Z. P., and G. R. Barsch, Nonlinear pressure dependence of elastic constants and fourth-order elastic constants of cesium halides, *Phys. Rev. Lett.*, **19**, 1381, 1967.
- Chang, Z. P., and G. R. Barsch, Pressure dependence of the elastic constants of single-crystalline MgO, *J. Geophys. Res.*, **74**, 3291, 1969.
- Chung, D. H., and G. Simmons, Elastic properties of polycrystalline periclase, *J. Geophys. Res.*, **74**, 2133, 1969.
- Daniels, W. B., and C. S. Smith, The pressure variation of the elastic constants of crystals, in *The Physics and Chemistry of High Pressure*, p. 50, Gordon and Breach, New York, 1963.
- Drickamer, H. G., R. W. Lynch, R. L. Clendenen, and E. A. Perez-Albuerne, X-ray diffraction studies of the lattice parameters of solids under very high pressure, in *Solid State Physics*, vol. 19, edited by F. Seitz and D. Turnbull, p. 135, Academic, New York, 1966.
- Gilvarry, J. J., Temperature-dependent equations of state of solids, *J. Appl. Phys.*, **28**, 1253, 1957.
- Gilvarry, J. J., Temperature correction to Birch's equation of state, *J. Appl. Phys.*, **33**, 3596, 1962.
- Grüneisen, E., Theory of the state of solids (in German), *Ann. Phys.*, **39**, 257, 1912.
- Lazarus, D., The variation of the adiabatic elastic constants of KCl, NaCl, CuZn, Cu, and Al with pressure to 10,000 bars, *Phys. Rev.*, **76**, 545, 1949.
- McQueen, R. G., and S. P. Marsh, cited by F. Birch, in *Handbook of Physical Constants*, *Geol. Soc. Amer., Mem.* **97**, edited by S. P. Clark, Jr., 587 pp., 1966.
- McQueen, R. G., S. P. Marsh, and J. N. Fritz, Hugoniot equation of state of twelve rocks, *J. Geophys. Res.*, **72**, 4999, 1967.
- McWhan, D. B., Linear compression of α -quartz to 150 kbar, *J. Appl. Phys.*, **38**, 347, 1967.
- Murnaghan, F. D., Compressibility of media under extreme pressure, *Proc. Nat. Acad. Sci. U.S.*, **30**, 244, 1944.
- Murnaghan, F. D., in *Nonlinear Problems in Mechanics of Continua*, p. 158, American Mathematical Society, Providence, R. I., 1949.
- Murnaghan, F. D., *Finite Deformation of an Elastic Solid*, p. 73, Wiley, New York, 1951.
- Ruoff, A. L., Linear shock-velocity particle-velocity relationship, *J. Appl. Phys.*, **38**, 4976, 1967.

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