A NEW THERMODYNAMIC APPROACH INTO THE RHEOLOGY OF THE LOWER MANTLE

Vallianatos,F.

Technical University of Crete, Laboratory of Physics, Chania 73110, Crete, Greece.

A B S T R A C T

In the present paper we study i) the variation of the effective viscosity with depth and ii) the variation of the activation volume for creep, across the Lower Mantle. The calculations were made using the so-called cBΩ model, indicating that : i) the cBΩ model can reconcile a nearly uniform viscosity Lower Mantle (consistent with recent experimental data) if the rheology is non-Newtonian with constant strain rate, and ii) the activation volume for creep decreases by 50% from the top to the bottom of the Lower Mantle. A discussion of Weertman's empirical relationship is also performed.

ΜΙΑ ΝΕΑ ΘΕΡΜΟΔΥΝΑΜΙΚΗ ΠΡΟΣΕΓΓΙΣΗ ΣΤΗ ΡΕΟΛΟΓΙΑ ΤΟΥ ΚΑΤΩΤΕΡΟΥ ΜΑΝΔΥΑ

Βαλλιανάτος,Φ.

Π Ε Ρ Ι Λ Η Ψ Η

Σε σειρά προγενέστερων εργασιών η ρεολογική συμπεριφορά του Μανδύα εχει μελετηθεί κάνοντας την υπόθεση οτι για τον μηχανισμό της αργής ολίσθισης (creep), που είναι άμεσα εξαρτημένος απο το μηχανισμό της διάχυσης, η ενέργεια Gibbs G^{act} , είναι συνδεδεμένη με μακροσκοπικές παραμέτρους όπως το διατμητικό μέτρο ελαστικότητας ή το σημείο τήξης. Στην παρούσα εργασία μελετάται ι)η μεταβολή του ενεργού ιξώδους με το βάθος, και ιι) η μεταβολή του ενεργού όγκου $υ_{act}$ με το βάθος,στον Κατώτερο Μανδύα της Γης.Οι παραπάνω υπολογισμοί έγιναν με τη χρήση του προτύπου cBΩ. Οι υπολογισμοί δείχνουν οτι: ι) το πρότυπο cBΩ αναπαράγει ένα Κατώτερο Μανδύα με σταθερό ιξώδες, συμβιβαστό με πειραματικά δεδομένα, αν η ρεολογία του Μανδύα είναι μη-Νευτώνια με σταθερό ρυθμό παραμόρφωσης και ιι) ο ενεργός όγκος ελλατώνεται κατά 50% απο το βάθος των 770 Km εως το όριο Μανδύα-Πυρήνα. Τέλος, σχολιάζεται η εμπειρική εξίσωση του Weertman.

INTRODUCTION AND BACKGROUND

Because of its importance to mantle convection and other problems in geodynamics, numerous efforts have been made to estimate the viscosity of the Earth's mantle. It is accepted that the mantle must flow by solid-state creep (Stevenson and Turner, 1979)and hence the viscosity should depend on temperature

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

(through the activation energy) and on pressure (through the activation volume υ_{act}).

It is suggested by creep experiments (Weertman, 1970) that the rate of deformation in the Earth's interior can be expressed as:

$$\dot{e} = A\,\sigma^{v} \exp\left(\frac{-G^{act}}{RT}\right) \qquad (1)$$

where $\dot{e}$ is the strain rate , σ the deviatoric stress , G^{act} the Gibbs free energy of activation , T the temperature ,R the gas constant and A a constant . The effective viscosity η of the mantle $\eta=\frac{\sigma}{2\dot{e}}$ can be written (Poirier,1990) using eq(1) in one of the following three equivalent forms:

$$\eta = \frac{\sigma^{1-v}}{2A} \exp\left(\frac{G^{act}}{RT}\right) \qquad (2)$$

$$\eta = \frac{\dot{e}^{\frac{1}{v-1}}}{2A^{\frac{1}{v}}} \exp\left(\frac{G^{act}}{vRT}\right) \qquad (3)$$

$$\eta = \frac{(\sigma\dot{e})^{(1-v)(1+v)}}{2A^{\frac{2}{(v+1)}}} \exp\left[\frac{2G^{act}}{(v+1)RT}\right] \qquad (4)$$

Equations (2),(3),(4) express the viscosity in terms of stress, strain rate and strain energy dissipation rate, $\sigma\dot{e}$, respectively. We will estimate the depth dependence of lower mantle viscosity by assuming that :

$$\eta(z) = \eta(z_o) \exp\left[\frac{G^{*}(z)}{RT(z)} - \frac{G^{*}(z_o)}{RT(z_o)}\right] \qquad (5)$$

where $G^{*}(z)$ is the apparent activation energy equal to G^{act} , G^{act}/v , $2G^{act}/(v+1)$ for constant stress, strain rate, strain energy dissipation, respectively, and z_o is a reference depth (the top of the lower mantle). It is clear from (5) that to determine $\eta(z)$ we need to evaluate $G^{*}(z)$ and $T(z)$. We will estimate the lower mantle temperature $T(z)$ by assuming that it is adiabatic, as is appropriate for a vigorously convecting system and using the acoustic Gruneisen parameter γ to approximate the adiabatic temperature gradient.

To estimate the $G^{*}(z)$ or the $\upsilon^{act}(z)$ many authors (i.e Sammis et al.,1981; Ellsworth et al., 1985) use an elastic energy model originally developed by Zener (1949) and applied to point defects by Keys (1963) or an empirical connection between the

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

activation enthalpy and the melting temperature (melting point model), (Weertman, 1970; Ellsworth et al., 1985).

On the other hand the so-called cBΩ model was suggested (Varotsos and Alexopoulos, 1986). In this model they present a thermodynamically justified connection between defect parameters (like G^{act}) and macroscopic parameters of a solid. It is the purpose of this paper to apply the cBΩ model for the estimation of the viscosity in the Earth's Lower mantle, using elastic parameters.

CONNECTION OF THE GIBBS ENERFY WITH THE BULK PROPERTIES THE cBΩ MODEL

Varotsos and Alexopoulos (1986) suggested a thermodynamical model which connects the Gibbs energy with the bulk properties. According to this model, the Gibbs energy Gi is given by:

$$G^i = c^i \cdot B \cdot \Omega \qquad (6)$$

where B is the isothermal bulk modulus ,Ω is the mean atomic volume and c_i is practically a constant independent of temperature and pressure.For a given host lattice ci depends only on the mechanism i (i =activation,formation or migration) .

The reliability of (6) has already been checked for point defects in :

(a) various categories of solids (e.g alkali halides, silver halides lead halides metals rare gas solids, semicon- ductors), (Varotsos and Alexopoulos, 1986; Varotsos et al., 1988) and recently in liquid mercury (Vallianatos and Eftaxias, 1991).

(b) various defect processes (e.g formation, migration, and self diffusion).

The application of Zener formula leads to deviation from experimental data up to 50% for monoatomic crystals and fails for ionic crystals. In other words a comparison between the results obtained from Zener and cBΩ models indicates the superiority of cBΩ model (Varotsos et al., 1988; Vallianatos and Eftaxias 1993).

GEOPHYSICAL APPLICATION OF THE cBΩ MODEL

a. The variation of Gibbs energy with depth in lower mantle.

We estimate the Gibbs energy within the lower mantle using the expression $G^{act}=c^{act}$ B Ω , checking elsewhere for the case of power-law creep in olivine (Vallianatos and Eftaxias, 1993). It is evident from eq.(6) that a value of c^{act} has to be determined. In order to evaluate this value i.e $c^{act}= G^{act}/(B\ \Omega)$ we use the data presented by Graham (1970) for the density ρ and the isothermal bulk modulus B, respectively. In view of the uncertainties in the estimation of G^{act} (Ellsworth et al., 1985) and the influence of water in this values, we have used a minimum estimate of $G^{act}=(72\pm4)$Kcal/mole reported by Kohlstedt et al., (1980) . By inserting these values into eq.(6) we find $c^{act}=0.055$. In the calculation of the viscosity profile, the B and Ω values from the Preliminary Reference Earth Model (P.R.E.M) , (Dziewonski and Anderson ,1981) have been used. We also note that

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

we have approximated the isothermal bulk modulus B with the isoentropic bulk modulus Bs. They differ at most by a few percent which leads to a slight overestimate of $G^{act}(z)$. Fig.1 shows $G^{act}(z)$ for the lower mantle calculated from eq.(6) with $c^{act}=0.055$, using the data of P.R.E.M seismic model .

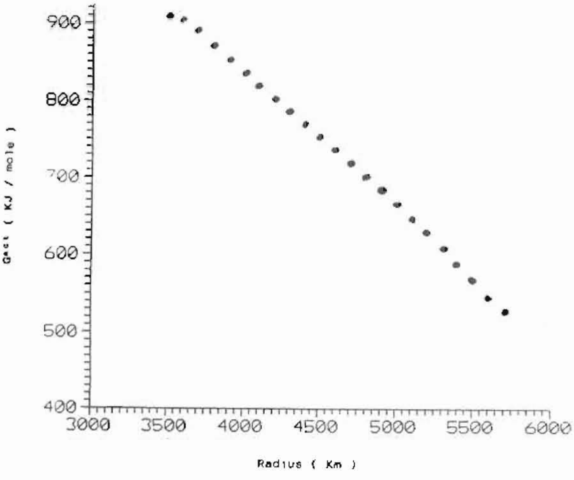

Fig.1. The variation of Gibbs energy G^{act} versus radius, calculated on the basis of the cBΩ model.

b. Lower mantle viscosity profile.

We proceed now to the estimation of the viscosity of the lower mantle through eqs. (2),(3),(4) by using the values of $G^{act}(z)$ from Fig.1 and the adiabatic temperature profile from Fig.2, given by Ellsworth et al., (1985), using the Gruneisen parameter and the assumption that the long wavelength acoustic vibration modes are characteristic of all modes (optic and short wavelength acoustic) so that the acoustical Gruneisen parameter gives a close approximation to the thermal Gruneisen parameter γ.

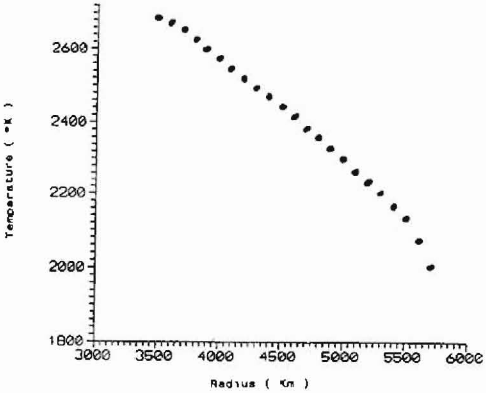

Fig.2. The adiabatic temperature profile (Ellsworth et al., 1985).

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

For the depth of 670 Km, we use the value T= 2000°K suggested by Akimoto et al., (1976) from phase transition experiments. Fig.3 shows the viscosity variation in the lower mantle, calculating according (5) with $G^{act}(z)$ from Fig.1 and the adiabatic temperature profile from Fig.2 . Results are shown for assumptions of constant stress, constant strain rate and constant strain energy dissipation rate in a power law fluid with ν=3. Viscosity increases with depth by a factor of 104 for the Newtonian lower mantle. The power law lower mantle viscosity with constant strain energy dissipation rate gives an increase in η with depth by a factor less than about 102 ; for constant strain rate the increase is by no more than a factor of about 20.

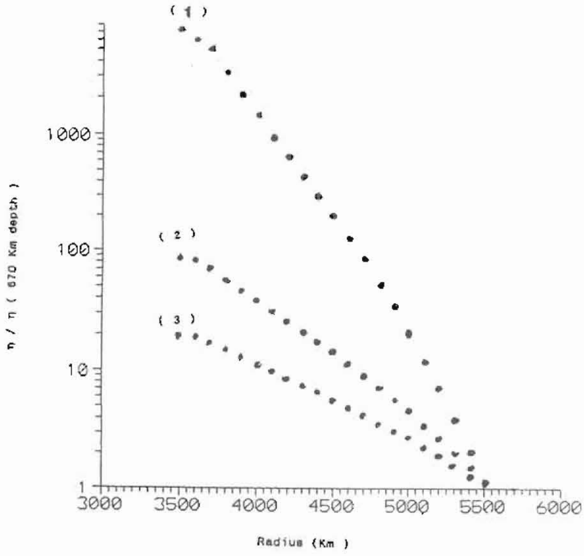

Fig.3. Variation of the effective viscosity η across the lower mantle, estimated using the cBΩ model for the calculation of G^{act} in Fig.1 and the adiabat in Fig.2. Line (1):constant stress, line (2): constant strain energy dissipation rate, line(3): constant strain rate. The calculations are based on a power law rheology with ν=3, (see the text).

c. Calculation of the variation of activation volume for creep with depth.

1) A direct application

By differentiation of eq(6) in respect to pressure and g^{act} recalling that

$$\upsilon^{act} = \frac{\partial g^{act}}{\partial P}\Big|_T$$

we get:

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

$$\upsilon^{act} = c^{act} \cdot \Omega \left(\frac{\partial B}{\partial P}_{|T} - 1 \right) \qquad (7)$$

A direct application of the last relation gives:

$$\frac{\upsilon^{act}}{\upsilon_o^{act}} = \frac{\Omega}{\Omega_o} \cdot \frac{(dB/dP_{|T}-1)}{(dB/dP_{|o}-1)} = \frac{\rho_o}{\rho} \cdot \frac{(db/dP_{|T}-1)}{(dB/dP_{|o}-1)} \qquad (8)$$

where υ^{act} ,Ω, ρ,dB/dP denote the activation volume, the mean molecular volume, the density and the pressure derivative of bulk modulus, respectively. Those labelled with the subscript " o " correspond to the values at the top of the lower mantle. The values of ρ and dB/dP are deduced from the available seismic velocites at various depths when the Preliminary Reference Earth Model (P.R.E.M),(Dziewonski and Anderson, 1981) is employed. Fig.4 shows the ratio $\upsilon^{act}/\ \upsilon_o^{act}$ versus the depth in the Earth's Lower mantle. We see that eq(8) reveals that the activation volume decreases by almost 50% in the lower mantle, thus making it easier to maintain constant viscosity in this region. This result is comparable to the values published up to date (Poirier and Liebermann ,1984).

2) Using the equation of state of Grover-Getting-Kennenty

Equation (7) leads to :

$$\frac{d\ln\upsilon^{act}}{dP} = -\frac{1}{B} + \frac{\frac{d^2B}{dP^2}}{\frac{dB}{dP}-1} \qquad (9)$$

The necessary values of d^2B/dP^2 are obtained from the following equation of state suggested by Grover ,Getting and Kennendy (1973),(GGK equation of state):

$$-B \cdot \frac{d^2B}{dP^2} \approx \frac{dB}{dP} \qquad (10)$$

and hence eq(9) reads:

$$\frac{d\ln\upsilon^{act}}{dP} = -\frac{1}{B}\left(1 + \frac{\frac{dB}{dP}}{\frac{dB}{dP}-1}\right) \qquad (11)$$

Using data from P.R.E.M,a numerical integration of (11) leads to the values of $\upsilon^{act}/\upsilon_o^{act}$ inserted in fig.4 . The results obtained using (11) are compatible with those of the direct application of cBΩ. The latter indicates that the combination of cBΩ model with the Grover,Getting and Kennendy equation of state gives satisfactory results for the ratio $\upsilon_{act}/\upsilon o^{act}$ in the Earth's lower mantle (see fig.4).

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

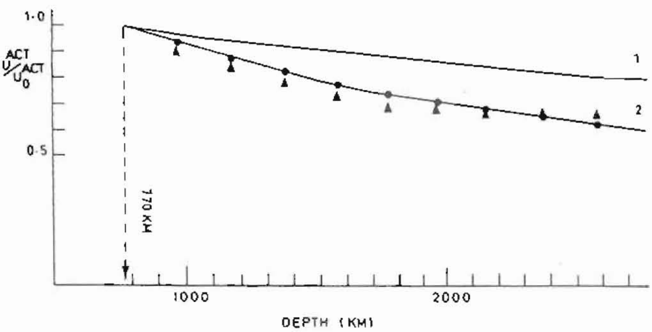

Fig.4. Relative decrease of the activation volume with depth for various models;(1) Karato (1981), (2) Poirier and Liebermann (1984). Circles represent values from the combination of the cBΩ model and the GGK equation of state. Triangles represent values from the direct application of the cBΩ model.

4) Comments on Weertman's empirical relationship between viscosity and melting temperature.

A working <u>empirical</u> equation in Geophysical literature is that called Weertman's relationship:

$$\eta = \eta_o \exp\left(\frac{\alpha T_M(p)}{kT}\right)$$

where η denotes the viscosity at pressure p and temperature T η_0 a proexponential factor, α an empirical constant, while the subscript M denotes the temperature at the melting point. From a physical point of view, eq.(12) is a straightforward result of the well known empirical law that the experimental activation enthalpy scales with melting temperature i.e $h^{act}_{exp} = \alpha$ TM .The experimental scaling factor " α " for silicates has a value of arround 30 k as reported by Poirier and Liebermann (1984).

We shall proceed to the explanation of the above mentioned empirical law on the basis of cBΩ model. This model leads to the expression (see Varotsos and Alexopoulos ,1986):

$$\frac{s^{act}}{h^{act}_{exp}} = -\frac{\left.\frac{d(B\Omega)}{dT}\right|_P}{B_o^{SL}\Omega_o} \qquad (13)$$

where s^{act} the activation entropy, Ω_o the mean atomic volume at zero temperature and $B_o^{SL} = B - T\,(dB/dT\,|P)$ the point of intersection of the linear part of B(T) with the vertical axis.

$$h^{act}_{exp} = \left(\frac{S^{act}}{A}\right)\cdot T_M \qquad (14a)$$

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

For materials that have an almost linear connection detween BΩ and T up to melting point (i.e temperature independent values of enthalpy and entropy), the derivative $d(B\Omega)/dT|P$ can be approximated by [BM ΩM - $(B_o\ \Omega_o)^{SL}$]/ TM. By considering also that Ω_o^{SL} Ω_o eq(13) can be written as where

$$A=1-\left(\frac{B_M}{B_o^{SL}}\right)\cdot\left(\frac{\Omega_M}{\Omega_o}\right) \qquad (14b)$$

The necessary sact values in (14a) can be estimated from the relation (Varotsos and Alexopoulos , 1986):

$$\frac{S^{act}}{\upsilon^{act}}=-\frac{\beta B+\left(\frac{dB}{dT}\Big|_P\right)}{\frac{dB}{dP}\Big|_T-1} \qquad (15)$$

Obviously the combination of (14a),(14b) and (15) leads to the calculation of the proportionality factor between hactexp and TM provided that υ_{act} is known. For the case of olivine the elastic data B , dB/dT and dB/dP from Graham (1970) are used for the calculation of BM and BoSL . The activation volume has been experimentally estimated by Kohlstedt et al., (1980) and the melting temperature reported by Sammis et al., (1981). For the quantites ΩM / Ωo and β a rough estimation of 1.1 and 3 10-5 K-1 used,respectively (Anderson et al.,1968). A straightforward calculation leads to the value 27 k for the constant " α ". This calculated value is comparable to the aforementioned experimental value of 30 k. One should note that Weertman's empirical law is an approximation and the condition of its applicability are not known ; we have seen that it holds whenever BΩ decreases linearly with T and hence the activation enthalpy and entropy are temperature independent (Vallianatos and Eftaxias,1992).

DISCUSSION

The scope of the present paper is the application of cBΩ model (which connects the activation Gibbs energy to bulk properties) to Geophysical problems.

We have applied first the cBΩ model to the estimation of the activation Gibbs energy G^{act} ,versus depth,in the Earth's Lower mantle. In accordance to this model the quantity G^{act} can be calculated using only the bulk modulus and the density parameters that can be evaluated from Seismic Earth Models. Secondly we estimate the effective viscosity of the lower mantle, using the cBΩ model to estimate G^{act} and the density dependence of the Gruneisen parameter to calculate the adiabatic temperature profile. Our estimates of the effective viscosity η of the lower mantle depend on the dynamical and rheological state of the lower mantle. Increase in η with depth range from a factor of about 7 10^3 for power law flow with constant stess to about 20 for non-Newtonian deformation with constant strain rate and 100 for constant strain energy dissipation rate.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

On the other hand analysis of post-glacial rebound (Cathles, 1975; Peltier,1981) and the true polar wander (Nakiboglu and Lambeck, 1980; Sabadini and Peltier, 1981; Sabadini et al., 1982 ; Yuen et al., 1982) suggest that the effective viscosity of the mantle is relativly constant with depth despite the sensitive temperature dependence of the Earth's viscosity and the increase of T with depth. The latter indicates that among all the testing models only a non-Newtonian lower mantle, convecting with constant strain rate is consistent with recent estimates of mantle viscosity from post-glacial rebound and true polar wander data.

As it has been already mentioned, we have chosen the lowest reasonable value of G^{act} in order to estimate c^{act}. Repeating the calculation for an increase of G^{act} (e.g by 30%) to a more realistic activation energy, we can see that only the case of constant strain rate is still consistent with constant viscosity lower mantle.

Second we apply the cBΩ model to the process of solid state creep, for the calculation of the ratio $\upsilon_{act}/\upsilon_o^{act}$ versus depth in the Earth's lower mantle. This ratio can be calculated when using only the pressure derivative of the bulk modulus and the density, parameters that can be evaluated from seismic earth models. We also calculated the relative variation of activation volume, as it results from the combination of cBΩ model with the equation of state proposed by Grover et al.,(1973).In both cases the activation volume is found to decrease by 50 % from the top to the bottom of the lower mantle. The latter value is in agreement with the results obtained by Poirier and Liebermann (1984) but in contrast to those of Karato (1981).

The compatibility of our results to those of Poirier and Liebermann (1984) can be seen as follows:in order to estimate the ratio $\upsilon^{act}/\upsilon_o^{act}$,the latter authors used the expression

$$\frac{d\ln\upsilon^{act}}{dP}=-\frac{1}{B}\cdot\left(1+\frac{\gamma}{\gamma-\frac{1}{3}}\right)$$

where γ is the thermal Gruneisen parameter. Equation (16) however can be derived from the cBΩ model: Anderson (1979) and Brennau and Stacey (1979) suggest that for the lower mantle the Gruneisen parameter varies with pressure as the atomic volume and so

$$\gamma\cdot\rho=constant, \qquad \frac{\partial\gamma}{\partial P}=-\frac{\gamma}{B}$$

A combination of eq (9),(17) with Slater expression for the Gruneisen parameter (γ = - 1/6 + 1/2 dB/dP) leads to eq(16). We turn now to the discussion of the results obtained by Karato (1981) who assumed that

$$\frac{d\ln\upsilon^{act}}{dP}=-\frac{1}{B} \qquad (18)$$

By comparing eq.(18) and (11) we see that they differ by the last term of the right side of eq.(11). Therefore the two equations coincide only in case when dB/dP = 0 , i.e in the case of a

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

harmonic solid. In the case of real solids however the quantity dB/dP has usually values between 3.5 and 8 (Romain et al.,1976). For the case of olivine, a rough estimation of the quantity (dB/dP)/(dB/dP - 1) gives values of the order of 1.3 . These remarks might explain the under-estimation of the value of $dln\upsilon_{act}/dP$ by Karato (1981),(see fig.4) ,

CONCLUSIONS

By summarizing the results of the present paper we can state that the cBΩ model :

(1) gives reliable estimations of the variation of the activation volume of creep with the depth in the lower mantle

(2) leads to an understanding of the empirical value of the proportionality factor used in the Weertman's law.

(3) can reconcile a nearly uniform viscosity lower mantle with current estimates of G^{act} and the mantle adiabat if the rheology is non-Newtonian with constant strain rate.

REFERENCES

Akimoto,S.E., Kamada,E. and Kushiro,I., (1976). Effect of pressure on the melting of olivine and spinel polymorph of Fe2SiO4 , J. geophys. Res.,72: 679-686.

Anderson, O.L., (1979). Evidence supporting the approximation γ ρ = const. for the Gruneisen parameter of the Earth's lower mantle . J. Geophys. Res., 84:3527-3542 .

Anderson,O.L., Schreiber,E., Liebermann,R.C. and Soga,N., (1968). Some elastic constant data on minerals relevant in geophysics. Rev. Geophys., 6:491-523.

Brennau,B.J. and Stacey,F.D., (1979). A thermodynamically based equation of state for the lower mantle. J. Geophys. Res., 84:5535 - 5539.

Cathles,L.M., (1975). The viscosity of the Earth's Mantle. Princeton University Press.

Dziewonski,A.M. and Anderson,D.L., (1981). Preliminary reference Earth model , Phys. Earth Planet. Inter., 25 : 297-356.

Ellsworth,K., Schubert,G. and Sammis,C.G., (1985). Viscosity profile of the lower mantle , Geophys. J.R. Astr. Soc., 83 : 199-213 .

Graham,E.K., (1970). Elasticity and composition of the Upper mantle , Geophys .J.R. Astr. Soc., 20 : 285 - 302.

Grover,R.,Getting,I.C. and Kennedy,G.C., (1973). Simple compressibility relation for solids. Phys. Rev.B,7:567-571.

Karato,S., (1981). Rheology of the lower mantle. Phys. Earth Planet. Inter., 24 :1-14 .

Keyes,R.W., (1963). Continuum models of the effect of pressure on activation processes , in Solids under Pressure, pp. 71-99, eds Paul,W. and Warschauer,D., McGraw Hill, New York.

Kohlstedt,D.L., Nichols,H.P.K. and Hornack,P., (1980). The effect of pressure on the rate of dislocation recovery in olivine, J.Geophys. Res., 85 : 3122-3130.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.

Nakiboglu,S.M. and Lambeck,K., (1980). Deglaciation effects on the rotation of the Earth , Geophys. J.R.Astr. Soc., 62: 49-58.
Peltier, W.R., (1981). Ice age geodynamics , Ann. Rev. Earth Planet Sci., 9: 199-225.
Poirier,J.P., (1990). Introduction to the Physics of the Earth's interior , pp. 150-151, Cambridge University Press Cambridge.
Poirier,J.P. and Liebermann,R.C., (1984). On the activation volume for creep and its variation with depth in the Earth's Lower Mantle. Phys. Earth Planet. Inter.,35:283-293.
Romain,J.P., Migault,A. and Jacquesson,J., (1976). Relation between the Gruneisen ratio and the pressure dependence of Poisson's ratio for metals . J.Phys. Chem. Solids ,37:1159-1165.
Sabadini,R. and Peltier,W.R., (1981). Pleistocene deglaciation and the Earth's rotation: implications for mantle viscosity, Geophys. J.R. Astr. Soc., 66 : 553-578.
Sabadini,R., Yuen,D.A. and Boschi,E., (1982). Polar wandering and the forced response of a rotating multilayered viscoelastic planet, J. Geophys. Res., 87: 2885- 2903.
Sammis,C.G., Smith,J.C. and Schubert,G., (1981). A critical assesment of estimation methods for activation volume, J. Geophys.Res., 86:10707 - 10718.
Stevenson,D.J and Turner,J.S., (1979). Fluid model of mantle convection . In M.W. McElhinny (Editor), The earth: its origin and evolution. Geophys. Space Phys., 8:145-168.
Vallianatos,F. and Eftaxias,K., (1991). A comment on the pressure dependence of the viscosity processes of the liquid state , Acta geophys. Polonica , 39/2 : 233-238.
Vallianatos,F. and Eftaxias,K., (1992). The application of the cBΩ model for the calculation of the variation of the activation volume for creep with depth in the Earth's lower mantle , Phys. Earth Planet. Inter., 71:141-146.
Vallianatos,F. and Eftaxias,K., (1993). Analysis of thermodynamic point defect parameters of geophysical interest, 2nd Congress of Greek Geophysical Union (poster).
Varotsos,P. and Alexopoulos,K., (1986). Thermodynamics of point defects and their relation with bulk properties,pp 451, eds. Amelinckx , S., Geners , R. and Nihoul , J., North Holland , Amsterdam.
Varotsos,P., Eftaxias,K. and Hadjicontis,V., (1988). Defect parameters obtained from positron-annihilation and self-diffusion experiments in silicon, Phys. Rev. B., 38 : 6328-6332.
Weertman,J., (1970). The creep strength of the Earth's mantle, Rev. Geophys. Space Phys., 8 : 145 -168 .
Yuen,D.A., Sabadini,R. and Boschi,E.V., (1982). Viscosity of the lower mantle as inferred from rotational data , J. Geophys. Res., 87 : 10745 - 10762.
Zener,C., (1949). Relation between residual strain enerdy and elastic models, Acta Crystallogr., 2: 163-166.

Ψηφιακή Βιβλιοθήκη Θεόφραστος - Τμήμα Γεωλογίας. Α.Π.Θ.