CHAPTER I

INTRODUCTION

Earthquakes occurring at different geographical locations are associated with the evolution process of the planet Earth. The seismic elastic waves that sample the interior of the Earth travelling from its sources to the recording stations, provide the only informations which when analysed can reveal to a great extent, the internal properties and structure of the deep interior. Two very important parameters, primarily the compressional and shear wave velocity distributions inside the Earth, can lead to the determinations of the different properties like density, viscosity etc. Another parameter known as Q (or Q^{-1}), related to the attenuation of the seismic waves, tells a good deal about the behaviour of the materials within the Earth's interior and also provides a measure of its anelastic properties including the thermal and physical states

Although the earthquakes continue to be the major sources of data for these studies, the nuclear explosions also have now emerged as a prime and most sought after sources on its own right due to some of its advantages, such as their correct locations, time of occurrences, energy yield, etc. Over and above these, it has also facilitated the use of the seismic phases that arrive later than the first phase which helps to reduce some of the ambiguities that result when a seismic structure is constructed on the basis of only the first arrivals. Adequately used, seismic waves from both these sources have yielded enough informations about the properties of the interior of this planet.

1.1 Seismic study : a brief review :

The increasing number of sophisticated instruments like short period and long period seismometers, gravimeters, tiltmeters, strain gauges etc. have now helped the seismologists to collect the informations about the interior of the earth. The development of the long period instruments for the study of the long period surface waves, free oscillations and normal mode data have helped in suplementing the informations already collected earlier. The advent of the fast digital computers have given a new wind to these studies.

Yet the old classical methods of the study of the travel time, the first arrival time of the body waves at a recording station, the S-P time intervals, amplitudes and spectral analysis etc. have helped in developing a fairly good model on the structure of the earth's interior, which happens to be the basic foundation of the present day seismology.

The study of the travel times by the old classical methods have more or less accurately fixed the two first order discontinuities at the crust-mantle boundary (first suggested by A. Mohorovičić in 1909) at an average depth of 30 Km and the core mantle boundary roughly at 2900 Km depth, although, this is also not free from the regional variations like all the parameters about the interior of the earth. For example, the depth of the Mohorovičić discontinuity varies from 50 - 60 Km in central Asia, about 45 Km in north America, 31 - 34 Km in Alaska, about 35 Km in south Africa and around 10 - 11 Km in the oceanic areas (Richter,1958). Similarly the depth of the base of the mantle although seem to be fairly close to 2900 Km as suggested by Oldham and Gutenberg in 1906 and 1912 respectively, some of its recent values seem to be around 2898 ± 3 Km due to Jeffreys (Bullen,1967), 2890 Km (Johnson , 1969), 2885 Km (Busse,1983) etc. Following Bullen's division of the earth on seismic evidences, including Byerly's (1926) "20° discontinuity", Dahm's, Repetti's, Lehman's and various other studies (Mercy,1967), the mantle region is divided into three basic layers as B,C and D; the lowermost D region being approximately known as the lower mantle, starting around 800 Km depth (Anderson,1967). The evidences from the seismic travel time studies (Niazi and Anderson,1965; Green and Hales, 1968;Lewis and Mayer,1968; Johnson,1967; Kanamori,1967; Rautian et al.,1978; Radmacher et al.,1983) have fairly established the large scale heterogeneities (though small but significant) in the B and C regions, supporting the findings of a large number of early workers including Byerly, Gutenberg, Oldham, Repetti, Lehman etc. (Bullen,1967). Bullen, however, found the velocity variations in the D region, at least within 1000 - 2700 Km to be steady and normal, with a sharp fall in the last 100 - 200 Km subsequently necessitating a sub-division of this region into D' and D" (Bullen,1967).

The study of the travel time data ultimately culminated in the development of the models of the earth suggested by Gutenberg and Jeffreys (Press,1966) and a standard travel time table due to Jeffreys and Bullen (1958).

1.2 P wave velocity and lower mantle heterogeneity :

The earlier velocity distribution of Jeffreys and Gutenberg shows a smooth variation of velocity throughout the lower mantle, although there were some suggestions, as early as 1928, by Repetti about the presence of some discontinuities at various depths including the "Repetti discontinuity" at 970 Km (Johnson,1969) in the lower mantle region. But studies taken up later (Chinnery and Toksöz,1967; Hales et al.,1968a; Johnson, 1969) raised serious doubts about the homogeneity of the lower mantle. Some of the suggested discontinuities to date include that due to Repetti, who observed abrupt changes in velocities at 32.2°, 39.4°, 65° and 77.5° and by Vvedenskaya and Balakina at 38°- 42°, 51°- 53°, 70° and at about 80° from a study of the ratio of P waves to SH waves and SV waves to SH waves (Anderson, 1967; Johmson,1969). There are others also suggesting the levels of anomaly at 39°, 52°, 69°, 79.5° and 89.5° (Carder,1964), 53° and 59°(Hales et al.,1968a), 35°, 53° and 70°(Chinnery and Toksöz,1967) and also at 34.5°, 40.5°, 59.5°, 70.5° and 81.5° (Johnson,1969) epicentral distances. Although these findings do not match in finer details, yet, considering the possible regional variations, they give ample evidences against the lower mantle homogeneity. It was Julian and Sengupta (1973) who put forward first a considerable body of evidences suggesting the depth dependence of the lower mantle heterogeneity and also identifying the region near the core mantle boundary as most heterogeneous, later again confirmed by another study (Sengupta and Toksöz,1976). Dziewonski (1984) used a set of data (about 500,000 travel time residuals from 5,000 events) with time - term approach for deriving an aspherical P velocity model for the lower mantle. The model represents strong velocity perturbations of 1 - 1.5% just below the 670 Km discontinuity and just above the core mantle boundary with less perturbations near 2000 Km depth. The anomalies though seem to be small in comparison to those in the crust and the upper mantle, the role played by them become quite significant when they are used to determine the other properties like density, elastic constants etc. (Dziewonski et al.,1975). A sizable velocity discontinuity at the top of the D" layer (~2700 Km), with large anomaly comparable to the upper mantle, has also been suggested (Lay,1987).

Geomagnetic data indicates thermal perturbation at the base of the mantle (McFadden and Merril,1984). Constancy of the ratio of the mantle temperature to the corresponding Debye temperature, derived using the Grüneisen function in the lower mantle, indicating the adiabaticity of the region (Anderson, 1979), penetration of the upper mantle materials into the lower mantle with some stratification around 1500 Km depth or deeper and also recycling of the continental crust and oceanic crust materials through the mantle (Davies,1984) and higher silica content in the lower mantle region (Liu,1979) have also been advocated pushing the idea of the lower mantle heterogeneity very far.

1.3 Anisotropy of the mantle :

The attenuation of the seismic energy inside the earth is generally expressed by a parameter Q known as the quality factor. This factor also helps to visualise the anelastic properties of the materials inside, controlled by thermal and defect properties influenced by thermal conductivity, grain size, defect concentration and mobility, diffusion rate and / or the relatively weak interatomic and interdefect bonds at grain boundaries (Jackson and Anderson,1970).

Attenuation mechanisms on crustal rocks has been reviewed by Knopoff (1964) and by Gordon and Davies (1968), who found that in polycrystalline samples a hysteresis type of attenuation might occur from the friction at the grain boundaries. Knopoff and McDonald (1958) and Carpenter (Andrews and Shlien,1972) have developed linear viscoelastic models for Q, which they found to be constant over a broad frequency band.

The factor Q (or Q^{-1}) measuring the dissipation of the seismic energy by absorption, scattering or through other mechanisms is indicated by the amplitude variations of the seismic waves. However, the seperation of the effects of the source and the path on the seismograms of an earthquake is one of the basic problems in seismology as regards the path effects (attenuation) at the crust and the upper mantle including the effect at shallow depth below the recording site called the site response. The ratio Q_p/Q_S gives an idea about the difference in attenuation mechanism between the asthenosphere and the upper lithosphere (Frankel,1982; Rautian et al.,1978a; Anderson et al.,1965). Another technique of analysing amplitude of long period surface waves successively passing through a station to find attenuation free from the above effects, have been used successfully by Anderson and Archambeau (1964), Anderson et al. (1965), and have shown that the factor Q for the shear waves in the earth's mantle is considerably higher in the lower mantle than in the upper mantle. Kovach and Anderson (1964) and Anderson and Kovach (1964) used ScS and sScS phases to determine Q for near normal incidence from deep focus earthquakes yielding almost similar results. An attempt by Anderson (Knopoff 1967) to correlate the Q^{-1} for viscosity distribution for upper mantle showed that the viscosity of the lower mantle is high. Sipkin and Jordan (1979) using core ScS phases noted the frequency dependence of Q_{ScS}. A period dependence of inner core Q_S has also been observed by Anderson and Given (1981) who also found low Q at the seismic band at both top and the bottom of the mantle. Nakamura and Koyama (1982) also observed frequency dependence of lunar Q_p and Q_S and a decrease of Q_p from stable value and an increase of Q_S with the increase of frequency.

However, Q is generally assumed to be independent of frequency for short period waves at small range of frequencies. Teng (1968) used short period P pulses from deep focus earthquakes, assuming the frequency independence of Q within 0.01 - 0.2 cps. He used spectral ratio technique to eleminate the source and geometrical spreading effect and constructed a model (F or G), which shows a low Q in the upper mantle region and gradually increasing to about 1900 Km depth and then decreasing towards the base of the mantle. He fixed the Q factor at 100 near the base of the mantle, the last 200 Km having an average Q of about 150. Mula (1981) found Q_{α} not to be less than 250 at the base of the mantle for long period P waves.

The Q factor determined so far gives widely varying results depending upon the type of waves and the range of frequencies used. For example, Kanamori (1967a,b,c) found the values of Q to be 410 - 630 for the whole mantle, 180 - 240 above 870 Km and 1600 - 6000 below 870 Km depth for P waves of period 0.8 - 2.5 secs. Kovach and Anderson (1964) and Anderson and Kovach (1964) determined the average values of Q for the whole mantle that fell in the range of 588 to 500 for shear waves of period 10 - 50 secs. Takano (1971) on the other hand found average Q_{β} to be around 800 $\pm$ 60 and average Q_{α} to be around 2000 $\pm$ 120 for period range 0.1 to 1.0 sec. For P waves of frequency range 0.4 - 1.0 Hz, Choudhury (1972) found $T/Q_{\alpha} \equiv 1$ at 53°, 73° and 85° epicentral distances. From a study of P wave spectra, Mohammadioun (1967) found indications of absorbant region between 650 and 950 Km, 1800 and 2000 Km and at 2900 Km depth. A similar feature of low Q (absorbant region) is also reported by Sarmah (1973) near 950 - 1000 Km depth corresponding to about 40° epicentral distance.

Jackson and Anderson (1970) had summarised in detail the values of Q found by different workers using body waves, surface waves and free oscillation data. Recent studies on short period P waves show consistent frequency dependent models for the attenuation factor (Lay, 1987; Cormier, 1982). PcP and ScS core phases studies (Bolt and Canas, 1985; Choy and Cormier, 1986) although do not show a low Q zone near the base of the mantle, a recent model (Shore, 1986) has such a feature like some earlier models. Low Q values with increased velocity heterogeneity in the D" region points to the scattering effect of the crust and the lithospheric materials present there due to gravity settling (White and Hoffman, 1982; Davies, 1984).

The "650 Km discontinuity", starting well below 700 Km with high silica content (Liu, 1979) and with an observed density jump of about 7% (Hart et al., 1976) probably acts as a thermal and/or chemical boundary layer, precluding the idea of the whole mantle convection (McKenzie and Weiss, 1975; McKenzie and Richter, 1981). A double layer mantle convection model with a quadrupolar convection mode is also suggested (Busse, 1983). On the basis of the global gravity and seismic data and density distribution, the most likely cause of the lower mantle heterogeneity is thought to be due to the convection in the lower mantle.

1.4 The present study :

Here, an attempt has been made to study the distribution of P wave velocity and Q with depth in the lower mantle within 30°- 90° epicentral distance range.

A study of the surface waves gives more reliable informations about the heterogeneity of the crust and the upper mantle. However, the difficulties one faces about the interpretations of the surface wave and normal mode data are that they are functions of both shear and compressional wave velocities and density. Hence all global studies on the lateral heterogeneity of the lower mantle relied more on the travel time anomalies of the body waves (Dziewonski,1984), since they make the most direct measurment of the physical properties like elastic constants, density, composition etc.

The aim of this study will be to find a P wave velocity distribution with depth corresponding to the 30^{o}- 90^{o} epicentral distance range from the first arrival P wave travel time curves from four locations of nuclear explosions in USA and USSR and one each, shallow, medium and deep focus earthquakes in the northern and southern hemisphere. Another objective of this study is also to find the distribution of Q with depth from the four nuclear events and the two shallow and deep focus earthquakes from different regions of the earth's surface so that samples of the parameters can be obtained covering major parts of the earth. The P waves from earthquakes of magnitudes around 6 or larger, of course, are generally complex and the source time function of nuclear explosions and earthquakes of equivalent magnitudes are different. However, Choudhury (1972) has shown, from the comparison of the negative spectral slopes of the two types of events, that when frequencies higher than 0.4 Hz are used, these complexities can be avoided since in that case only the rise time of the signal will mainly be analysed. So he utilised a frequency band of 0.4 to 1.0 Hz in his study, which has been followed in this study also.

In the present work simple inversion methods, used successfully by some workers, are used to obtain the velocity - depth and Q - depth distributions as mentioned above. The results so obtained are then compared with those of others.

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