6.1 INTRODUCTION

It is well known that compressional and extensional seismic waves in the crust exhibit significant regional variations. P-wave and S-wave travel time propagating from focus with equal time independent of azimuth show different characteristics in various regions. The seismic signal which is recognized as the first arrival depends on the crust – upper mantle structure between source and receiver, instrumental magnification and the noise levels at the recording site. Simple technique involving the earthquake data, including Wadati-Riznichenko diagrams allows one to resolve the tradeoff in origin time and focal depth. Estimates of the average half space velocities for P- and S-waves, and of the travel time ratio \((T_s/T_p)\) helps to understand the material property of the upper crust. A comprehensive variation of velocity of P- and S-wave arrivals with depth can be regarded as the path and site specific inhomogeneities between the source and receiver. Moreover, the technique i.e. the Wadati diagram depends only on the observe arrival times of P- and S-waves and is completely independent of any parameters used in the hypocentral location procedure. The ratio of a P-wave velocity over an S-wave velocity offers important information on the physical properties of the continental crust. The \(V_p/V_s\) ratio of crustal rocks are mainly controlled by the mineral contents of plagioclase with high Poisson ratio and silica with low Poisson ratio. The presence of crustal fluids of partial melting form a high \(V_p/V_s\) ratio because shear wave velocities diminish more at the presence of fluids within the upper crust than compressional wave velocities hence observation regarding \(V_p/V_s\) ratio could help to gain a better understanding about the characteristics of crust and researchers have used \(V_p/V_s\) ratio to infer the property of the crust.

In this chapter, an emphasis has been made to observe the variation of \(V_p/V_s\) ratio for shallow earthquakes recorded at close distances within the seismogenic zone in Surma valley along selected depths ranges to identify and to obtain reasonable physical properties of the crust underneath. Simultaneously how the valley is related to its adjoining region, so far as the physical properties among the regions are concerned, becomes useful in identifying gross lateral changes within the region.
6.1.1 Velocity Ratio (Vp/Vs)

The P-wave velocity is determined using the data of direct P arrivals. The T\text{p(obs)} \text{i.e.}, observed P arrival for an earthquake can be written as:

\[ T_{\text{p(obs)}} = T + + T + \text{ORG} \]

where T = P wave travel time, ORG = origin time of the earthquake, and + T = the time correction which incorporates the error due to changes in elevation and/or geology of the seismograph stations.

P-wave velocity is then determined from the slope on a plot of T\text{p(obs)} versus hypocentral distance (distance between station and earthquake focus). Similarly S-wave velocity is also determined from S-wave arrival times.

Basically, as the first step, Wadati method is used for getting model independent estimates of travel times of P- and S-waves to various stations. From these estimates, the origin time of earthquakes as well as S-P travel time ratios are obtained. For this purpose, differences in arrival times of S and P phases are plotted against P arrival times for each earthquake.

The most direct method to estimate the Vp/Vs ratio with seismic data is to utilize travel times of P- and S-waves from crustal events. Both travel time of P- and S-waves are of great importance as these contribute to the knowledge of regional crustal structure immediately. The principal techniques involve the use of Wadati (1933) and Riznichenko (1958) diagrams as shown in Figure 5.1 (in Chapter-V). Both the methods have had a long history of use as primary tools in the earthquake location process. Wadati diagrams are used for determining origin times of regional earthquakes (Bune et al., 1960). The Wadati diagram is based on the linear relationship between the arrival time of P (Tp) and the time differences between P and S (Ts-Tp) for different recording stations for an earthquake as follows:

\[ Ts–Tp=(Tp–To)(ts/tp–1) \]

which brings forth an intercept that is an estimate of the origin time (To) and a slope that is a function of the average travel time ratio (ts/tp).
The linear relation produces a slope that is a function of the average half-space velocity \( v \). Following the Soviet practice (Bune et al, 1960), a plot is made on the log of the travel time against distance to lay emphasis on travel times to the nearer, more important stations.

These methods have the advantage because of their simplicity and robustness. The Wadati diagram depends only on the observed arrival times of P- and S-waves and is completely independent of any parameters used in the hypocentral location procedure. Normally, the Riznichenko diagram requires estimates of the origin time \( (To) \) and the epicentral distance \( (+) \). The origin time as determined from the Wadati diagram and distances as calculated from the trial computer location are used in practice. When stations are well distributed in azimuth around the epicenter, distances are generally well controlled. Velocities of P- and S-waves can then be easily determined. Estimates of focal depths can be used to identify cases where compensating errors in depth and origin time have constrained the focal depth to remain near the starting depth used in the computer location program.

The velocity information these methods provide is useful in a number of other ways. The techniques of Wadati and Riznichenko serve a number of uses in the routine processing of micro earthquakes locations; hypocenters can be checked for proper convergence; simple earth model can be developed; spatial variations in ts/tp can be mapped; focal mechanism solutions can be improved; and regional variations in velocity can be identified (Nicholson and Simpson, 1985). Of course their most common application has been to resolve the tradeoff in origin time and focal depth. Nicholson and Simpson (1985) find these methods have proved useful in a more fundamental sense of identifying significant earth structure and improving the general understanding of material properties of the upper crust.

The knowledge of physical properties of the crust, both upper and lower, can be made through proper estimation of \( V_p \) and \( V_s \). In order to estimate the velocity of P- and S-wave, the travel time of P- and S-waves to stations and the corresponding epicentral distances are required. With an initial location of earthquake and origin time computed from Wadati’s method, travel time P- and S-waves \((t\text{-}tp; t\text{-}ts)\) are computed. Variation of \( t^2 \) with \( x^2 \) is plotted for a number of stations. A least square fit
is obtained which helps to determine the respective velocity of the wave with the following equation

\[ t^2 = \frac{x^2 + h^2}{v^2} \]  

Where \( h \) is the depth of focus, \( x \) is the epicentral distance and \( v \) so computed is average velocity that is estimated.

The \( Vp/Vs \) ratio ranges between 1.69 to 1.75 in upper to lower crust. These differences in \( Vp/Vs \) ratio may be caused by lithological variations with depth. The variation of \( Vp/Vs \) ratio could be correlated with the geotectonics of the study area. A contour mapping of \( Vp/Vs \) could be made possible along different depth sections.

6.1.2 Previous Work on Estimation of P-Wave and S-Wave Velocities in NER

Several researchers worked towards the estimation of P-wave travel times in the studied region. One of such studies is that of Tandon (1954). From a study on the body waves of the great Assam earthquake of 15\(^{th}\) August 1950 and its 54 aftershocks, he derived the crustal structure in the Assam region. He has obtained the following velocities for \( Pg, P^* \) and \( Pn \) Waves: 5.58, 6.55 and 7.91 km/sec respectively. Assuming a mean depth of 13 km and using the intercept times, he obtained total crustal thickness of 46.3 km with 24.8 and 21.5 km thick upper and lower crust.

Sitaram et al., (1986) investigated the upper mantle velocity by teleseismic Pn arrival by using time-term method described by Scheidegger and Willmore (1957) and Willmore and Bancroft (1960) and found that the sub-Moho P-wave velocity exhibit a variation from 7.85 to 8.08 km/sec. Simultaneously, Kayal and De (1987) studied the seismic velocity of the uppermost mantle beneath the Shillong Plateau by applying the similar time-term method for the Pn arrivals of local earthquakes recorded by establishing temporary micro-earthquake networks and reported high mantle velocities (8.1-8.5 km/sec) beneath the Shillong plateau. In another study, De and Kayal (1990) estimated the upper crustal P-wave velocity by the time-distance plot method by using the P arrival data of the shallow (\( \leq 20 \) km) earthquakes in Shillong and Nowgong areas. They determined the upper and lower crustal P-wave velocity as 5.55 km/sec and 6.52 km/sec respectively using P arrival data of the shallow (\( \leq 35 \) km) earthquakes. Also, Baruah (1995) attempted to construct the crustal velocity model for NER India from the travel time analysis of body waves. Under a
Department of Science and Technology sponsored mult-institutional project, Rai et al., (1999) used the time-term method (Kind, 1972; Hearn, 1984) to compute the Pn velocities and found that it varies from 8.3 to 8.5 km/sec beneath the Shillong-Mikir Hills and Assam valley area. In 1998, Kayal and Zhao first attempted to determine P- and S-wave tomography images of the crust and upper mantle beneath the Shillong plateau using temporary micro-earthquake network data obtained from seven to eight temporary seismograph stations and they reported lateral heterogeneities in the crustal velocity structure beneath the Plateau. Similarly, Sitaram et al., (2001) estimated the crustal velocity model below the Brahmaputra Valley region by travel time analysis of Pg, P* and Pn waves. They also reported that the average Pn velocity is of the order of 8.0 to 8.5 km/sec and the depth of the Moho in the fore deep region is found to vary between 42 to 45 km. Bhattacharya et al., (2008) attempted to estimate 3D P-wave velocity structure of Northeast India region using the first arrival data of local earthquakes that were recorded by 77 temporary/permanent local seismic stations and they reported significant lateral as well as depth variation of velocity structures beneath the studied region. Presently, seismic activity in Northeast India is being monitored by state of the art digital seismograph network by various organizations. The data accrued from these stations allowed few researchers to adopt receiver function analysis technique (Kumar et al., 2004; Mitra et al., 2005 and Ramesh et al., 2005) to estimate the depth of Moho.

In regard to velocities of P-wave along propagation path involving major portion in Arakan-Yoma subduction region, Gupta et al. (1990) have analyzed travel times and estimated Pg and Pn velocities (km/sec): (1) 5.64, 7.99; (2) 5.11, 7.83; and (3) 5.99 for the path to KOI, YYI and KHM stations. By analyzing the travel times for the earthquakes in various zones around Shillong Seismic Station, Khattri et al. (1988) have obtained apparent Pn-velocities (km/sec): 8.69±0.8 and 7.8 to 8.25 in a NW direction towards Myanmar respectively. Using the time term method (Scheidegger and Willmore, 1957 and Willmore and Baucroft, 1960) Sitaram et al. (1988) have determined the inter-station velocities of Pn waves as 7.89-8.0 km/sec for Northeast India. Using the same method Sitaram et al. (1990) have analyzed the travel times for NER and derived Pg, P* and Pn wave velocities (km/sec): 5.64±0.34, 6.53±0.031 and 7.82±0.07 respectively. In general, differences in velocity estimates
may be attributed to the method of treatment and propagation paths moving the different tectonic elements.

6.2 DATABASE

P- and S-wave arrival time data from shallow and intermediate depth earthquakes recorded by selected seismic stations network in the Northeast during 1982 to 2009 are used for this study. Origin time, epicentral coordinates (latitude and longitude) and depth of the earthquakes were determined using the HYPOCENTER computer program of Linert et al. (1986). For initial location of the microearthquakes the velocity of upper crust (0-20 km) was assumed to be 5.5 km/s and the lower crust (21-40 km) to be 6.5 km/s and the mantle (below 40 km) to be 8.1 km/s.

The reconstructed travel time of P- and S-waves versus epicentral distances obtained from the best linear fit of Wadati and Riznichenko diagrams derived in Chapter-V are used to determine the ratio of the velocity of Vp/Vs versus depth in Surma valley and its vicinity comprising the upper crust beneath Mat fault area in the eastern part and Sylhet fault area in the northern part.

The P- and S-wave velocities determined from the reconstructed arrival times are used for the estimation of crustal velocity model in Surma valley and its vicinity from the earthquake events as relocated in Chapter IV. Depth ranges are selected at 20 km intervals and the parameters are distributed accordingly.

In addition, a set of 20 earthquakes are used for determination of Vp and Vs associated to Mat fault region at different depth ranges and 19 earthquakes are used for determination of Vp and Vs in Sylhet fault region at different depth ranges respectively. Certain standards were used to select the earthquakes for this set; firstly, the P and the S phases should be well recorded by at least five stations; secondly, the earthquake should occur within the study area and; finally, the reading of P and S phases should be accurate one which has been explained in detail in Chapter-IV.

6.3 Vp/Vs WITH DEPTH

The use of micro earthquakes to determine the orientation of active faults, focal mechanism solutions, and details of local crustal structure strongly depends on the velocity model used in the earthquake location process, and, as a consequence is
subjected to systematic errors introduced by inappropriate model parameters. With the advent of digital data and the increasing use of three-component stations, accompanied by additions of new stations in the Northeast, a large numbers of good quality P- and S-wave arrivals are being recorded. Separate velocity structure for P-wave is necessary if accurate and realistic earth model is to be determined. While employing the principal technique that involve the construction and analyses of Wadati and Riznichenko diagrams, we intend to obtain travel time ratio (ts/tp) at upper crustal depths and origin times that are independent of crustal velocity model and based on which the P-wave travel times as a function of epicentral distance are derived so as to obtain the velocity ratio (Vp/Vs) in the upper crust beneath study area inclusive of Mat fault and Sylhet fault region.

The data for the Wadati plot method are selected on the basis of the following criteria: (i) earthquakes are located within the seismic network (ii) the spatial distribution of earthquakes is as uniform as possible in the study area (iii) the events must have at least four S-P time intervals, (iv) the rms (root mean square) residual for events must be 0.5 sec or less, (v) P arrivals must have a residual of 0.5 sec or less and S arrivals 1.0 sec or less and (vi) the range of P arrival times must be greater than 4 sec.

The epicentral map of the earthquakes recorded during the above surveys is shown in Figure 4.1. The study area is divided into two regions: the northern part of Surma valley in the Bengal Basin and the eastern part of Surma valley in the Indo-Burmese arc. About 20 arrival times from earthquakes in region belonging to Mat fault area and 19 arrival times from earthquakes belonging to Sylhet fault region are used for the P-wave velocity study. The time-distance plots are as shown in Figures (5.2 – 5.8) in Chapter-V. Table 6.1 indicate the earthquake events to find out the velocity of P- and S-waves at selected depth ranges of 0-20 km, 21-40 km and 41-60 km respectively. Certainly variation in Vp/Vs ratio is observed at different depth sections. Although the variation is consistent among depth sections, it is inconsistent among two active faults in the region.

Apart from the estimations pertaining to the two faults, the lateral variation of Vp/Vs ratio at three distinct depth ranges are also observed for the Surma valley and the adjoining region.
6.4 RESULTS AND DISCUSSION

The Vp/Vs ratio down to a depth of 60 km from the obtained P- and S-wave travel times is computed. Vp/Vs ratio has been estimated by dividing Vp by Vs using the results obtained from Wadati and Riznichenko diagrams. It uses direct P- and S-waves with predominant frequencies of ~10 Hz, with the spatial scale of the heterogeneity in velocity structure. The Vp/Vs ratio so estimated are distributed among the depth ranges of 0-20 km, 21-40 km and 41-60 km respectively. Comparison of P-wave velocity estimates as reported by various investigators for Himalaya and Northeast India with the present study is shown in Table 6.2.

The Vp/Vs ratio for the Surma valley and its vicinity are distributed over the range 1.67 to 1.79 (Fig. 6.1). A highly inconsistent variation of Vp/Vs ratio is observed among three depths sections as well. In depth range of 0-20 km, Vp/Vs ratio is higher in the region bounded by latitude 22.5° to 23.5° and longitude 91.5° to 92.5° while rest of the region is characterized by dominance of lower Vp/Vs ratio. The scenario changes abruptly in case of the depth range 21-40 km. In this range, Vp/Vs ratio is least in the region bounded by latitude 25.5° to 24.5° and longitude 90.5° to 92.5° while the region near the latitude 24.5° and 91.8° indicate the highest dominance of values of Vp/Vs ratio. The distribution of Vp/Vs ratio is typical so far the depth range of 41-60 km is concerned. Lowest dominance of Vp/Vs ratio are observed in the eastern part of the Surma valley however the region with higher Vp/Vs ratio remains the same as observed in the depth range of 21-40 km. These variations obviously characterize the heterogeneity of the crust at different depth sections.

Simultaneously the distribution of Vp/Vs ratio are also observed in Figure 6.2 a,b,c for Mat fault region (eastern Surma valley) in different depth ranges. The velocity ratio (Vp/Vs) are found to be varying between 1.75 to 1.83 in 0-20 km depth range. However no remarkable variation is observed with the increase of depth up to 20 km (Fig. 6.2a). A notable variation in Vp/Vs ratio against increase in depth is observed in the depth range of 21-40 km. The Vp/Vs ratio is found to be consistently increasing with increase in depth up to 40 km. In the depth range of 40-60 km, a
sudden change in velocity \( V_p/V_s \) ratio is observed at a depth between 53 km and 54 km where it changes from 1.7 to 1.75.

Figure 6.3a and b depict the distribution of \( V_p/V_s \) in the northern part of Surma valley which is traversed by Sylhet fault. In Figure 6.3a, in the depth range of 20-40 km, a highly inconsistent nature of the velocity is observed at approximately 33 km depth where the velocity takes a sharp bend. The velocity ratio \( (V_p/V_s) \) suddenly decreases from \(~1.77\) to \(~1.7\) at this depth. This behavior of the sudden decrease in velocity maybe due to the in-heterogeneous nature of the crust. In the depth range of 40-60 km (Fig. 6.3b), however, a more or less uniform velocity is observed throughout the range where \( V_p/V_s \) ratio is at approximately 1.78.

In Mat fault region (eastern Surma valley) the variation is in the order of 1.74 (21-40 km) and 1.73 (41-60 km) whereas the average velocity-ratio \( (V_p/V_s) \) values for Sylhet fault region (northern Surma valley) in different depth ranges are 1.72 (21-40 km) and 1.75 (41-60 km) (Table 6.3). Similar spatial variation in velocity ratio \( (V_p/V_s) \) has been reported by Agarwal et al. (1975) and Kayal (1982) in other parts of the world. In this study no spatial variation of \( V_p/V_s \) is observed either for shallow (upper crust) or for deeper (lower crust) earthquakes. The differences in the \( V_p/V_s \) ratio are possibly caused mainly by lithological variations with depth.

Velocity of seismic waves varies depending on many physical conditions. Composition, saturation condition, temperature and ambient pressure play an important role in velocity variations. Composition may be more fundamental than the other factors because it is an intrinsic property of the local rocks. The differences in velocity among layers as shown in Table 6.1 may be caused by the differences in rocks composing each layer. It is well known that seismic velocity decreases as temperature increases (e.g. Fielitz, 1971; Sato et al., 1998). Fielitz (1971) measured as P- and S-wave velocity variations in different rocks at pressures of 400 MPa as a function of temperature. His result implied a different temperature dependence of Poisson’s ratio for the rocks investigated. On the other hand, Kern and Richter (1981) measured Poisson’s ratio for several rocks at a constant pressure of 600 MPa but with temperature varying from 20°C to 700°C and they concluded that Poisson’s ratio did not change much with temperature; the average increase in Poisson’s ratio for their rock samples was \(~1\%\), within experimental error. It is difficult to precisely evaluate
the effect of temperature on the Vp/Vs ratio in the crust and the uppermost mantle because there have not been systematic laboratory measurements carried out under the temperature and pressure conditions at those depths (Nakajima et al., 2005).

On the basis of above findings a generalized model related to the distribution of Vp/Vs ratio of the area is suggested (Figures 6.2-6.6). In order to achieve the model the P- and S-wave velocity and Vp/Vs ratio of upper crust and lower crust for both the fault regions (Mat and Sylhet) are determined in this study.

It is proved unexpectedly difficult to obtain entirely consistent P and S models. It is apparent that some of the difficulty arose from uncertainty with regard to the depth of the focus. While trying to reduce the uncertainty, it was noted that the ratio of the travel time ts/tp for S- and P-wave follows a pattern and the pattern remains unchanged to some extent subject to the observation made at different depth sections. To be specific enough Vp/Vs ratios are observed in such a way that it could be established that some variations exist certainly when the depth increases. No remarkable variation in upper crustal region may be mainly due to the contribution of homogenous lithology specific to the region. However, variation in deeper depth could be due to the heterogeneous lithology existed in the region. Sometimes the locations of earthquakes are virtually independent of the origin time if a well set of earthquake events are distributed accordingly with respect to distance and azimuth. If however the observational data are confined to one or two quadrants the time of origin errors results in errors in the location as well as in the depth of focus (Lomnitz, 1977). The errors in times of origin, depth of foci and location contribute to the scatter in the travel times and obscure the determination of travel times and regional variations in travel times. Thus it is desirable that step should be taken to reduce the errors in times of origin. Until revised upper crustal travel time tables are prepared, times of origin determined from ts/tp will be useful as these depend only on the observed times since they are model dependent.

Vp/Vs ratio can, therefore, help to discriminate lithology. For instance the low velocity for the P-wave found for depth section 41-60 km in Mat fault region, could be produced by high velocity saturated material with high crack density. Sometimes, high velocity observed with low velocity ratio implies that the material is likely to have low crack densities, low intrinsic velocities and possibly higher effective stress