CHAPTER 1

Earth's Structure

Five billion years ago the planet Earth was formed as a large conglomerate. Immense amount of heat energy released by massive high-velocity bombardment of the meteorites and comets melted the entire planet. Since then the planet is cooling off and the process is continuing even today. During the cooling process denser materials, like iron from the meteorites, sank into the core of the Earth while lighter material, e.g. silicates, oxygen compounds and water from comets, rose near to the surface.

Studies of the Earth's structure over the last hundred years have proved that the Earth consists of several layers. Characteristic properties of each layer are different in terms of physical and chemical parameters. The chemical parameters, e.g. alkalinity, acidity, salinity etc., and the physical parameters, e.g. pressure, temperature, density and elasticity vary from layer to layer. The parameters of elasticity and density determine the seismic wave velocity, which normally is different for each of these layers.

From the study of the seismic wave velocity and density, the Earth has been subdivided into four main units (Fig. 1.1) namely the inner core, outer core, mantle and crust (Ritter, 2006). The equatorial radius of the Earth is 6378 km, out of which the inner core is about 1250 km, the outer core 2200 km and the mantle is 2900 km thick respectively. The core is composed mostly of iron and is so hot that it's outer part (outer core) is molten, with about 10% sulphur. The inner core is under extreme pressure and remains solid. Most of the Earth's mass is in the mantle, which is composed of iron, magnesium, aluminium, silicon and oxygen compounds. At over 1000 degrees Celsius, the mantle is solid but can deform slowly in a plastic manner. The crust is composed of the least dense calcium and sodium/aluminium-silicate minerals. Being relatively cold, the crust is rocky and brittle and therefore is easier to fracture.

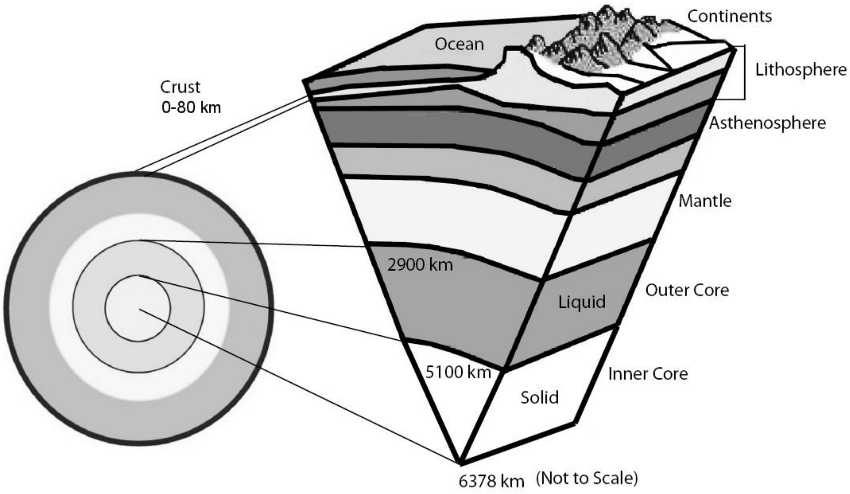

Fig. 1.1 Generalized structure of the Earth. Depths to major boundaries are given (modified from Ritter, 2006).

1.1 Lithosphere and Asthenosphere

The crust and the uppermost mantle, down to a depth of about 70-100 km under the deep ocean basins and 100-200 km under the continents, is called the lithosphere. It is rigid and forms a hard outer shell that deforms in an essentially elastic manner. The lithosphere is composed of various plates that float on partially molten asthenosphere. To delineate an unambiguous boundary that separates the lithosphere from the underlying asthenosphere has still not become possible. It is probably because the asthenosphere under old continental platforms is imaged as a broad zone in the seismic velocities. Here, instead of a single low velocity zone a series of high and low velocity layers are intermingled (Fuchs et al., 1987).

The upper mantle plays a crucial role in structural development of the Earth's crust. Critical levels of thermodynamic conditions prevail in individual zones of the upper mantle, under influence of differential and thermo-elastic stresses. A discontinuous increase or decrease of volume takes place due to polymorphic, phase and chemical transformation of the inhomogeneous mantle substance. Distribution of structural forms within the Earth's crust and mineral deposits on the surface have a close dependence on the processes occurring in the upper mantle.

The asthenosphere is a rheologically weak, semi-viscous layer in the upper mantle. In this layer the velocities often decrease suggesting lower rigidity. This weaker layer is thought to be partially molten; the melt may be able to flow over long periods of time like a viscous liquid or plastic solid, in a way that depends on its temperature and composition. The asthenosphere plays an important role in plate tectonics, because its viscous state allows relative motion of the overlying rigid lithosphere plates. Some of the researchers suggest that the asthenosphere should be defined not as a weak upper mantle layer, but as a zone of partial melting (Pavlenkova, 1988).

The lithosphere is divided into several plates, of which the crustal component could be either continental or oceanic. Very little progress has been achieved, so far, to understand the evolution of the continental lithosphere due to inaccessibility of its subcrustal part for direct studies. Explosion seismology studies in different tectonic settings (viz. old Precambrian shields, young continental platforms and the oceans) show that several velocity layers exist in the upper mantle (Mooney and Meissner, 1992). The most important findings are: 1. occurrence of the low velocity layers at shallow depths in the continental upper mantle, with large velocity contrasts at their boundaries and 2. observation of unexpectedly high compressional (P) wave velocities, up to 8.6-8.9 kms^{-1}, and high velocity gradients of 0.02--0.04 kms^{-1} at depths of 10-30 km below the crust-mantle boundary (Bean and Jacob, 1990). These findings provide indirect evidence that the elastic anisotropy continues within the uppermost mantle.

The crust covers the mantle and is the Earth's hard outer shell, the surface on which we are living. Compared to other layers of the Earth the crust is much thinner, like a stamp on a football. It generally consists of solid material, but this material is not the same everywhere, and is less dense and more rigid than the material of the Earth's mantle. The crust over the oceans is different in nature as compared to the rocks of the continental crust. The oceanic crust is about 6-11 km thick and the rocks in it are very young, not older than 200 million years, compared to the rocks of the continental crust. Its igneous basement consists of a thin (about 500 m thick) upper layer of superposed basaltic lava flows underlain by basaltic intrusion, the seated dyke complex and the gabbroic layer. A greater part of the oceanic crust consists of the tholeiitic basalt (basalt without olivine) that has a dark, fine and gritty volcanic structure. It is formed out of liquid lava, which cools off quickly. The grains are so small that they are only visible under a microscope. The average density of the oceanic crust is 3000 kgm^{-3}.

The crust under the continents and areas of shallow seabed close to their shores (continental shelves) is called the continental crust. It covers more than one third of the Earth's surface. It is thicker than the oceanic crust, 35-40 km thick under the stable areas and 50-80 km under the young mountain ranges, and mainly consists of igneous rocks. It is divided into two layers. The upper crust mainly consists of sediment, gneiss, granite and granodiorite rocks while the lower crust consists of basalt, gabbros, amphibolites and granulites. The average density of the upper crust is 2700 kgm^{-3} while that of the lower crust is 2850 kgm^{-3}. It is older than the oceanic crust; some rocks are as old as 3800 million years. When active margins of the continental crust meet the oceanic crust in subduction zones the oceanic crust is subducted due to relatively lower density of the former. The lower density does not allow the continental crust from being subducted or recycled back into the mantle. For this reason the oldest rocks on the Earth are within the cratons or cores of the continents, rather than in the repeatedly recycled oceanic crust. Increasingly younger units surround the older cores in the centre of the continents.

Six principal types of the crust are identified based on the sedimentary thickness, crustal thickness and mean seismic velocities (Belousov and Pavlenkova, 1985). Type I, in the regions of most recent mountains where high relief is accompanied by mountain roots, is 50-70 km thick. It has generally high heat flow values and mean velocities are in the range of 6.4-6.5 kms^{-1}, but in some sub types velocities as high as 7.0 kms^{-1} are also seen. Type II crust covers almost half the area of the continents and is common to areas with thin (< 3 km) sedimentary cover and also crystalline shields. It is about 40 km thick, mean seismic velocity in the consolidated part is around 6.5 kms^{-1}, and has low heat flow values. Type III is an attenuated, low-velocity crust in exterior parts of the continents, e.g. West European platform. It is 25-30 km thick, has an inconsistent heat flow and a mean seismic velocity of 6.1-6.3 kms^{-1}. Type IV is the transitional crust between the continents and oceans and is similar to Type III but has higher mean seismic velocity of about 6.6 kms^{-1}. It is observed in continental margins. Type V crust varies in thickness between 15 and 40 km and is associated with deep basins. It has large thickness of the sediments (5-15 km). The heat flow values are generally high and determination of its mean velocity is not possible. A typical feature of this type is presence of the high velocity lower crustal layers (> 6.8 kms^{-1}) and a lower thickness to the crust-mantle boundary. Type VI is the crust of oceanic basins where the crustal thickness is small and the upper part of the crust (granitic crust of velocity 6.0-6.3 kms^{-1}), whose thickness in the continental crust is in excess of 10 km, is absent.

The crust itself has no influence on the Earth but constant movement of the lithospheric plates (crust + uppermost part of the mantle), better known as the plate movement, caused by influence of the convection current in the asthenosphere does. To be more precise, the convection currents actually cause the Earth plates to move and sometimes collide with each other. These movements cause the Earthquakes and at weak zones of the Earth's crust the volcanoes can erupt. Because of ongoing plate movement in the last millions of years, the mountains and valleys have been formed, and that's why the surface of the Earth looks as it is now. Knowledge of characteristic features of the continental crust, therefore, is very important to understand the relationship between the processes in the Earth's mantle and the geological and geomorphological phenomena observed on the surface, as the present day configuration of continental crust is mostly an outcome of lithospheric evolution and crust-mantle interaction. This knowledge, together with the physical and chemical properties of the crust, is also vital to understand the mechanism of crustal evolution and tectono-thermal processes in the Earth's interior. It is also important for understanding characteristics of the earthquakes and other natural hazards, formation/distribution of the natural resources and evolution of various structural features present on the Earth's surface; as deep-seated structural variations in the crust are manifested in near surface geological pattern of direct human socio-economic interest.

1.2 Seismological Studies of the Earth's Crust

Due to essentially elastic behaviour of the continental crust all types of seismic studies, ranging from passive source seismic tomography to controlled source high resolution seismic reflection imaging, are preferred for gaining the knowledge of Earth's interior as compared to other methods. Strong lateral variation in structure of the Earth's crust and mantle make their study a complex problem. Virtually all of our direct information about interior of the Earth has been derived from studies related to propagation of the elastic waves generated by the earthquakes. The earthquakes generate two types of waves: the surface waves and the body waves. The surface waves are guided by the density and velocity layering, particularly at and near the surface, and are important in elucidation of the crustal and upper mantle structures. But of greater general interest and more easily understood are the body waves that propagate through the Earth. The compressional (P) and shear (S) waves that travel through the body of a medium are known as the body waves. The body wave in which the particle motion is in the direction of propagation is called the P-wave and the wave in which the particle motion is perpendicular to the direction of propagation is known as the S-wave. These conform to the laws of geometrical optics, being reflected and refracted at interfaces where the velocities change.

Historically, the seismological methods have provided first information about the crust. Among the oldest and most fundamental problems in seismology are: (a) determining the velocity-depth relation accurately, (b) asserting nature of the discontinuities within the Earth, and translating this into knowledge about interior of the Earth. Early in the 20th century study of the seismic waves, generated through the earthquakes, showed that interior of the Earth has a radially layered constitution and the boundaries between the layers are marked by abrupt changes in seismic velocities/velocity gradient. In 1906 Oldham noted that at large epicentre distance travel times of the seismic compression waves that traversed through the body of the Earth were greater than expected; the delay was attributed to a fluid outer core. Support for this idea came in 1914, when Guttenberg described a shadow zone for the seismic waves at distances of greater than 105^0 (1^0 = about 110 km at the equator). In 1936, Lehmann observed weak arrivals of the compression waves in the gap between 110^0 and 143^0 and interpreted it as an evidence for a solid inner core. An anomalous layer, 150-200 km thick and termed as ‘D’ layer, was identified just above the core-mantle boundary. In this layer the body wave gradients are very small and may even be negative. During 1940-42 Bullen developed a model, consisting of concentric shells, of the internal structure of the Earth. Later a parameterised model PREM (Preliminary Reference Earth Model) based upon the inversion of body waves, surface waves and free-oscillation data was prepared (Dziewonski and Anderson, 1981). This is the current standard model of the Earth’s internal structure.

Mohorovîcîc obtained first results of the crustal velocities in the year 1909. He identified a boundary at 30-35 km depth within the continents, where the seismic wave velocities in the Earth’s interior showed a sudden increase, and termed this as the crust–mantle boundary. This discontinuity, since then known as the Moho, is generally represented by either a large velocity jump or a steep velocity gradient (transition zone) in lowermost part of the crust and indicates a change from mafic to ultramafic rocks. In seismology the crust is defined by P- wave velocity (Vp) of lesser than 7.8 kms^{-1} or S- wave velocity (Vs) of lesser than 4.3 kms^{-1}, overlying an upper mantle with P-wave velocity of about 8.1kms^{-1}.

The earthquake studies identified three main P- wave phases in the crust: the Pg, PmP and Pn. The Pg wave follows the top of granitic crystalline basement below the sediments, the PmP wave appears as a critical or post-critical reflection from the Moho and the Pn wave is supposed to run along the top of mantle. In addition to these, other P - wave phases were also identified from various layers within the crust.

1.3 Controlled Source Seismic Study

The controlled source seismic study [also known as the deep seismic sounding (DSS) study] is a definitive geophysical technique for exploring structure of the Earth's crust and uppermost mantle. It is a highly sophisticated technique involving use of the controlled explosions, of known energy release, to generate the elastic waves in the Earth's crust. This method uses the technique of transmitting into the Earth the seismic waves that are generated by exploding charges and recording them back on the surface. Large success achieved by the seismic studies in hydrocarbon exploration prompted their use to study the Earth's crust. Through these studies the continental crust has been characterized by three broad parameters of its velocity, reflectivity and thickness. These parameters are also related to the heat flow, temperature and viscosity at various depths in the crust. The controlled source seismic study (5-30 Hz) effectively bridges the gap (Fig. 1.2) between the high frequency conventional exploration for hydrocarbon (30-100 Hz) and low frequency passive source seismological studies (0.1-5 Hz). For finding out the crustal structure it can be divided in two broad groups: 1) the refraction/post-critical (wide-angle) reflection also known as 'refraction seismology', and 2) the deep continental reflection study.

The most reliable information on velocity variation in the continental crust comes from the seismic refraction profiles. Though the variation of seismic velocity with depth can be fitted in five broad ranges (Meissner and Weaver, 1989), it differs according to the geology and tectonic configuration of a region (Table 1.1). Studies of the continental crust and sub-crustal lithosphere using seismic refraction/post-critical reflection measurements are of first order importance for determining reliable models of the seismic velocity structure and physical properties of the lithosphere. Eastern block of the European countries, led by erstwhile USSR, made major contributions to our understanding of the chemical and physical properties of the Moho through large scale refraction/post-critical reflection studies. The crust-mantle boundary (referred to as the Moho in forthcoming text) is regarded as the most important velocity boundary in the crustal seismic observations. General model of the continental Moho is a variable thickness transition zone, comprised of layers progressing from mafic to ultramafic rocks with increasing depth (Jarchow and Thompson, 1989).

Table 1.1 Velocity ranges in the crust (after Meissner and Weaver, 1989)

Part of the crust	Velocity (Vp) range kms^{-1}
Sediments or near-surface rocks	<5.7
Upper crust	5.7-6.4
Lower crust	6.4-7.1
Lowermost crust (in rifts, shields and platforms)	7.1-7.8
Uppermost mantle	>7.8

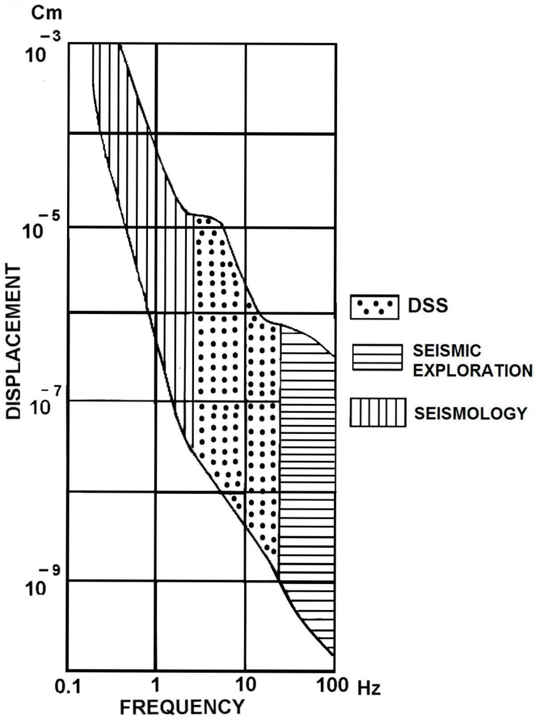

Fig.1.2 Schematic diagram showing the frequency range used in different seismic techniques.

The deep reflections (near-vertical incidence) from the Moho boundary were reported as early as late fifties but it took almost two decades to substantiate them through the deep continental reflection studies. The COCORP (Consortium for Continental Reflection Profiling, USA) studies paved the way in recognising the velocity layers as reflecting horizons and hence identifying the reflectivity patterns that determine structural variations in the crust of different geological terranes. Major deep seismic reflection study groups and consortia, e.g., BIRPS (UK), DEKORP (Germany), ECORS (France) and LITHOPROBE (Canada) followed it. High-resolution seismic reflection and refraction programs were also launched over the subduction zones (ANCORP Working Group, 1999), the arc-continent collisions along the continental margins (Lundberg et al., 1997), the convergent plate boundaries (Davey and Stern, 1990) and the orogenic belts (Snyder et al., 1997).

The seismic studies are capable of resolving shallow as well as deep structures in the crust by acquiring suitable refraction, post-critical reflection data sets and also near-vertical reflections. Advances over the past twenty years, both in the areas of seismic data acquisition as well as processing and modelling techniques offer wide-ranging possibilities to explore complex subsurface structures that may be heterogeneous and anisotropic. At present it is believed that combined refraction and deep reflection experiments (also known as coincident reflection studies) supported by the other geophysical, geological and geochronological studies on selected geo-transects provide the most reliable seismic images of the continental crust and uppermost mantle. The two seismic techniques are complementary to each other and when used together are capable of resolving the structural and physical property variations in the Earth. The refraction/post-critical reflection data sets provide viable models of the velocity distribution required to infer the petrologic composition, grade of metamorphism and material properties such as brittle/ductile regimes. These lead to consistent interpretation of the reflectivity patterns obtained through deep continental reflection studies and provide necessary clues for understanding the complex geodynamic processes that might be operative during the evolution of various geological provinces. In the tectonically active regions accurate mapping of the intra-crustal boundaries, including the Moho, and delineation of the deep penetrating steep/low-angle faults reveal various blocks in the crust that may have been relatively displaced due to movements along these faults.

1.4 Controlled Source Seismic Studies over the Indian Plate

India has a geologically unique position as rocks ranging from 3800 million years (Archaean) to the present (Quaternary) are exposed here. Geologists are of the opinion that several episodes of continental collision and extension have taken place during this time. However, history of the earlier episodes (from Archaean to Triassic) is not well documented. Geological history from the Triassic to the Quaternary time is much better understood. During the Triassic (about 210 Ma), a major rifting episode split the then existing Gondwanaland into two parts: East and West Gondwanaland. The Indian continent was in the East Gondwanaland together with Antarctica and Australia. The East and West Gondwanaland and the oceanic crust between them, were together till the Jurassic time (about 160-155 Ma). The Indian subcontinent then broke off from Antarctica and Australia in the early Cretaceous (about 130-125 Ma) and the Indian ocean opened up. During the upper Cretaceous time (about 84 Ma) the Indian plate started its very rapid northward drift at an average speed of 16 cmyr^{-1}, covering a distance of about 6000 km and a rotation of 33° in an anticlockwise direction, until the northwestern part of the Indian passive margin collided with Eurasia in Early Eocene (about 50 Ma). The Indian plate is still continuing its northward drift at a slower but still surprisingly fast rate of about 5 cmyr^{-1}. The tectonic map of India (Fig. 1.3) shows that the mobile belts separate various cratons from each other in its shield region (Vijaya Rao and Reddy, 2002).

Seismic studies based on the earthquakes have provided velocity-depth models for the crust and upper mantle of the Indian plate particularly the Himalaya, western part of the Indian shield and north eastern and central Indian region. These models based on the P- and S-wave structure, and also surface wave dispersion studies, have proved very useful in determining the earthquake parameters and seismicity pattern of the Indian subcontinent. In recent times teleseismic and tomographic studies have revealed the crustal and lithospheric thickness in various parts of the Indian plate (Rai et al. 2003, 2005).

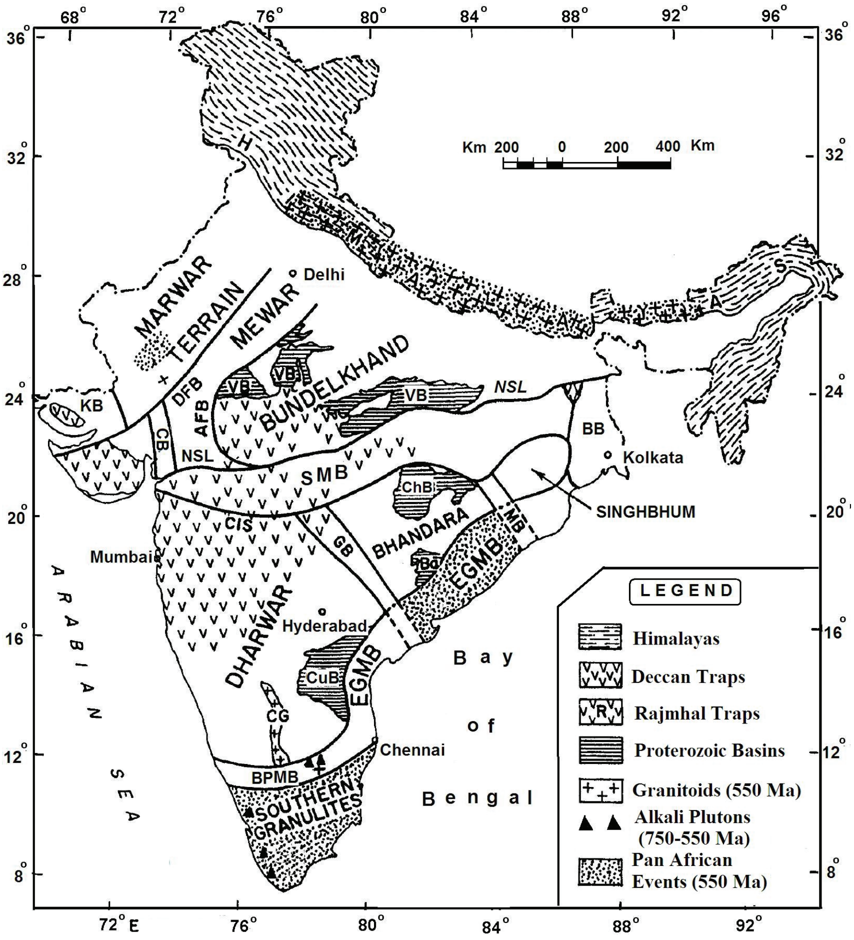

Fig. 1.3 Tectonic map of India. KB- Kutch basin, CB- Cambay basin, CuB-Cuddapah basin, ChB- Chattisgarh basin, DFB- Delhi fold belt, AFB-Aravalli fold belt, VB- Vindhyan basin, NSL- Narmada-Son lineament, SMB- Satpura Mobile belt, CIS- central Indian suture, BB-Bengal basin, MB- Mahanadi basin, GB- Godavari basin, EGMB-Eastern ghat Mobile belt, BPMB- Bhavani-Palghat Mobile belt, CG-Closepet Granite. (map source: Vijaya Rao and Reddy, 2002).

Though the seismological studies provide a gross picture of the crust, they are unable to detect the layering and also the velocity structure within it because of their low frequency range. The controlled source seismic studies were started in India in the year 1972 for a better understanding of the geological history of the Indian plate through the velocity and structural configuration of the continental crust. The National Geophysical Research Institute (NGRI), Hyderabad, India, has recorded a number of seismic profiles in different geological and tectonic provinces within the country. Between 1972 and 1985 all the crustal seismic data in India were acquired through the analogue seismic equipment. A major improvement in data acquisition took place when the digital units replaced the analogue equipment in the year 1985.

Between 1972 and 1991 only seismic refraction/post-critical (also known as wide-angle) reflection studies were carried out to understand the velocity models of the Indian crust. During this period major progress was made in processing of crustal seismic data sets due to their availability in digital form, leading to better data interpretation, in other parts of the world. Therefore another programme of digitising the earlier acquired data sets and their re-interpretation through the newer software packages was initiated. Acquisition of deep reflection data was initiated in the year 1992. Another milestone in data acquisition was achieved when wireless telemetry systems replaced the digital units in the year 1998. This made acquisition of crustal seismic data possible even in areas with difficult topography (e.g. Himalayan region). Since the data acquisition process for all types of seismic data is more or less similar and can be found in several textbooks, the same is not discussed here.

Under the programme to study the continental crust of India seismic refraction and post-critical reflection data sets were acquired along various profiles in different geological and tectonic provinces in the Indian shield (Peninsular shield, Southern Granulite Terrane, Aravalli-Delhi fold belt in the northwest), Narmada-Son Lineament in central India, Deccan Trap covered regions in the west), the sedimentary basins (Cambay, West Bengal, Mahanadi, Godavari) and Himalaya (Fig. 1.4). In some of the terranes (Aravalli-Delhi fold belt, central India, Southern Granulite Terrane, Himalayan foothills) the deep seismic reflection data were also acquired. Interpretation of these data has brought out the crustal velocity configuration and structure down to the Moho boundary, and occasionally in the uppermost mantle, leading to better understanding of the evolutionary processes involved in the formation of various terranes.

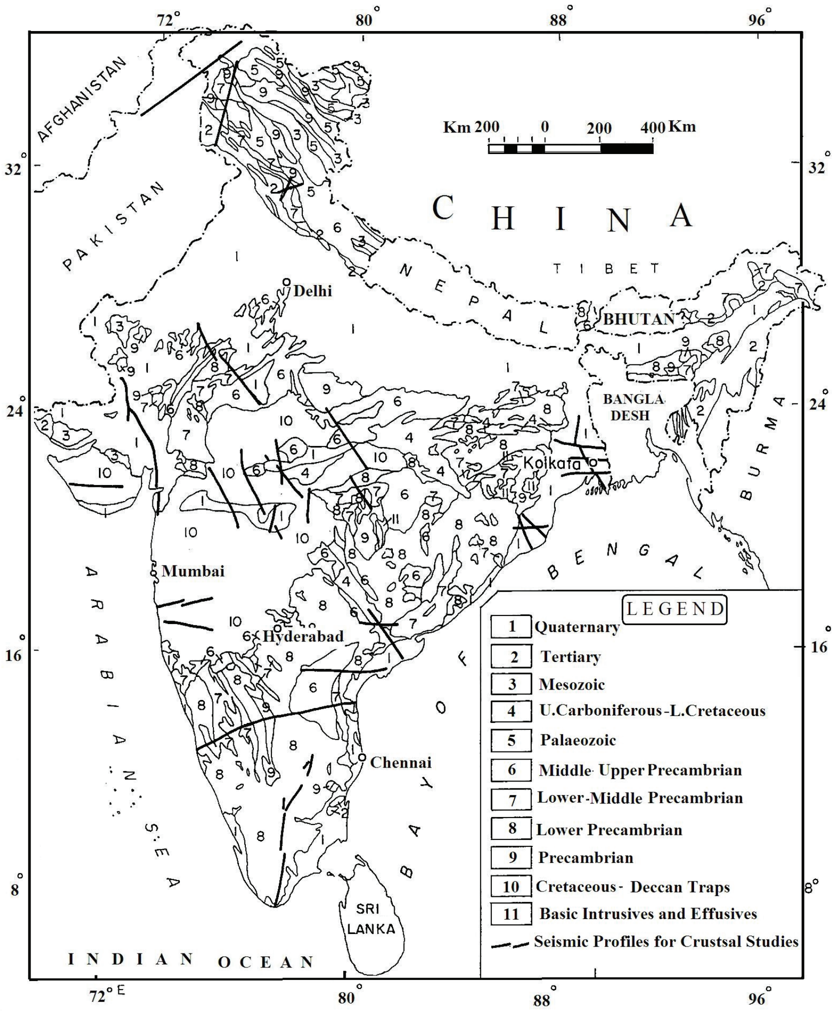

Fig. 1.4. Seismic profiles recorded to study the crust in the Indian subcontinent plotted on Geological Map of India. (Basic Map source: Geological map of India, Scale 1:5,000,000, 1993).

Outside the Indian plate seismic studies for understanding the continental crust have not been undertaken in the Southeast Asia except in Tibet and High Himalaya. Some of these have been included in this book. In the following chapters the results of various controlled source seismic studies carried out in India and its neighbourhood are described. Results from the other geophysical studies (e.g. passive source seismology, gravity and magnetic, magnetotelluric, heat flow etc.) have been described in brief wherever necessary.

The aim of this book is to make all these studies available at one place to enable the Earth scientists in India and abroad to be aware of them and their contribution in understanding the tectonic development of various geologic terranes in India and surrounding regions.