J. Ind. Geophys. Union (July 2012)
Vol.16, No.3, pp. 71-86

Historical development of seismic imaging technique – An Overview

P.R.Reddy
Scientist (Retd): National Geophysical Research Institute, Uppal Road, Hyderabad.
Home: 12-13-332, Street 12, Tarnaka, Hyderabad-500 017.
E-mail: rparvatareddy@yahoo.com; paravata@yahoo.com

ABSTRACT:
Old scriptures mention that early studies carried out by Rishis/sages have helped in developing various tools and techniques to unravel the mysteries associated with the Earth. Recognition of the ensuing events of disaster like storms, cloudbursts, fire etc. by prehistoric man was mostly done through sound and light waves .Like in the present day, his understanding of disasters like earthquakes was limited, as he was not having requisite knowledge to probe the interior of the earth. It is mentioned in some old scriptures that the ancient man tried to guess the location and onset of earthquake activity, from the unusual behaviour of some animals and insects.Varahamihira mentioned in Brihat Samhita that earthquake prediction can be done observing abnormal cloud formations. Specific details of their studies need to be extracted from earlier scriptures, to add to our knowledge base.

Even though sound waves have historically been used to understand vibrations of various frequencies, and to decipher signals coming from within the Earth, no systematic development in imaging the internal structure of the earth began until the mid 19th century. A concise exposition of the historical development of seismic imaging techniques is included in this article, to expose the reader to the focused studies carried out by eminent scientists of the 19th and early 20th centuries. The very fact that earlier studies combined theory and practice points out to the importance of these early studies and the strong scientific base they have created for subsequent developments. During the last 50 to 60 years considerable progress has been achieved not only in imaging basement structure but also sub basement crustal and sub crustal lithospheric structure. Theoretically supported experiments and their use in producing results help in holistically developing various scientific studies. Such a holistic development has been achieved in the seismic imaging of the subsurface formations extending from near surface depths to sub crustal columns. The basic objective in summarizing these chronological developments is to provide a broad understanding of the evolution and development of seismic imaging techniques (covering both analog and digital eras).Such an understanding is essential to properly use present day higher quality data acquisition and processing gadgets and would help producing high quality subsurface images, with time and space parameters as essential inputs. It is now well established that area specific attributes and time dependant variations alone can help in better understanding the intricate processes associated with subsurface structures and tectonics. The passive seismic based mega Arrays have indeed yielded excellent images of deep interior and provided useful information on the crust-mantle interactions. Global Array data and area specific 4-D seismic images of different dimensions, hopefully, would provide apt answers to many of the problems linked to the structure and evolution of the crust and sub crustal lithosphere.

1. INTRODUCTION

A) Pre Historic studies:

Study of vibrations in the Earth, now termed as seismology, began as far back as prehistoric times. Early man must have used his senses to hear and feel the vibrations resulting from natural disasters to learn ways and means for his survival , and also used these skills to hunt wild animals by tracking the vibrations created by herds. Our ancestors in India, using the technique of "Shabda Bhedi" (sound interceptor) created several useful and strategic weapons to intercept enemy congregations Unfortunately, accounts\writings of many such valuable innovations related to the science of sound vibrations and hence to the field of seismology were lost with time, leading to a vital gap in our knowledge base.

Figure 1. Chinese earthquake detector similar to the type first invented around 132 AD (as visualized by Wang Chen-To (1936)).

The earliest known earthquake detection instrument, used in imaging of earthquake resultant surface manifestations, was invented in China in the year 132 A.D. (Figure 1). The instrument was a simple bronze jar, with a pendulum inside. On the outside of the jar was placed a series of dragon heads connected to a pendulum, each with a ball in a hinged mouth. Directly beneath each dragon head, was a bronze toad with its mouth open to receive a ball falling from the dragon's mouth. During an earthquake, the ground motion would cause a ball to drop from a dragon's mouth into a toad's mouth. The direction of the earthquake would be judged by noting which of the dragon heads had dropped a ball. This instrument was sensitive enough even to perceive ground shaking too small to be felt and also for detection of even distant, as far away as 500Km., earthquakes events. (CERI, 2010).The observation of extent of shaking has helped in gross quantification of the magnitude of an earthquake. This in turn has indirectly helped in understanding the earthquake mechanism,viz, the extent of energy released and the extent of damage caused due to subsurface structural in-homogeneities and compositional variations. This instrumental development and utility enthused Chinese scientists to take up subsurface imaging studies. Specific results of these exercises however are not available. A relook into old manuscripts may throw light on these unknown, but highly useful results.

There is no authentic evidence of ancient Indians having developed any contraption similar to the contrivance of ancient Chinese (as mentioned above) to mark or observe shaking of earth due to an impending earthquake. However, interestingly one of the fundamental questions addressed by the ancient Indian philosophy concerns the source of primordial sound (Nad) similar to the Big Bang. Indian seers have tried to understand vibrations (Nad) of various frequencies that are both manmade and natural, to decipher various signals coming from the bowels of the Earth. In spite of significant developments in this technique by our ancestors, usage of sub surface signals was mostly confined to locating hidden natural resources of shallow origin, including ground water sources. Ancient scriptures suggest, the studies carried out by our ancestors have helped in location of shallow ground water sources. Varahamihira, the famous astrologer, in the classic book Brihat Samhita mentioned that one could predict earthquakes by observing abnormal cloud formations. Recently Taiwanese scientists Kuo et al(2011) have suggested that Ionosphere bubbles (Plasma Bubbles)are generated by pre-earthquake activity. They claim that ionosphere plasma bubbles and density variations are induced by pre-earthquake rock currents and associated surface changes. They have noticed electric coupling between the ionosphere and surface changes in the earthquake fault zone. They have further noticed a relationship between pre-earthquake build up of ionosphere bubble and formation of "Fox Clouds". Ancient astronomers have also suggested that abnormal planetary positions can exert gravitational pull on the earth, leading to earthquake activity. These details clearly establish that our ancient intellectuals have developed needed theories to predict earthquakes.

Besides these, the scientists and intellectuals of ancient times confined their studies particularly to aspects related to purification of air and water to safe guard the environment and to cure various ailments that were affecting the society. The Rishis wrote treatises on a vast number of subjects with such great insights and concepts that could not be fathomed or surpassed so easily, but surprisingly they made no effort to attach their own dates and stamps of personality to their studies/works. Even though such a practice resulted in our losing these valuable notes, the practice brings into focus the importance given to a study and not to the individual. The sages/Rishis knew that their brief life spans were only of temporary importance as flashes of the great infinite light; and the truth is timeless, impossible to trademark, and no private possession of their own (Autobiography of an Yogi)

B) Historical Development of imaging technique

With the advent of industrial revolution man has brought into reality the application of imaging technique, to locate the subsurface structures of importance to the mining and hydrocarbon industry. The technique has been successfully used from the mid 19th century.

Seismic imaging is multi-dimensional, and the scientists of early 19th century, closely looked at events and witnessed the effects of such events in order to develop various theories. For example, a stone thrown into a pond of water creates waves and observation of the resulting motions led intellectuals to develop wave propagation theories. They noticed that there is direct relationship between magnitude of the impact and the amplitude of the waves generated. They tried to measure these phenomenon related to the impact in different media. These initial observations were subsequently translated to produce meaningful models to understand the structure and composition of the medium that acted as the source for generating secondary wave propagation. Another analogy to explain the rate of energy transmission was explained by the example of an athlete who, in covering specific distances on different types of tracks took different times. The change and variation in the time spent to cover the same distance by the same athlete brought into focus the relationship between velocity and the energy involved in covering different tracks and the significant role of ' composition' of the track/medium of propagation.

It has been observed by many that when an earthquake occurs the resultant wave propagation, in general, is experienced in horizontal as well as vertical directions. From these motions, researchers have developed theories to explain primary and secondary wave propagation. The early researchers noticed that the damage due to the secondary wave propagation was typically greater, as the impact created by waves perpendicular to the direction of wave propagation is significantly more. The concept of secondary wave was first introduced by Ch. Huygens in 1690 while analyzing the reflection and refraction of light waves. Huygens achieved recognition for his argument that light consists of waves, now known as the Huygens–Fresnel principle, which became instrumental in the understanding of wave-particle duality. Fresnel (1818) refined Huygens theory and explained the linear propagation of light and introduced the concept of an all pervading elastic medium of ether. An alternative model of the refraction mechanism is proposed by Fresnel which is based on the scattering concept of light radiation by atoms. The effect of the body movement aberration on the scattering model was also presented by him. While the hypothesis of all pervading ether was later discarded with the advent of electromagnetic theory of light which served as an important source in developing the physics of sound waves which was later applied to seismic waves by Cagniard (1958) in his mathematical elucidation of "Reflection and Refraction of Seismic Waves".

In these days of working with the data on the state of the art computing facilities, it is often assumed that the output generated after computer analysis directly represents the actual result, which need not be the case always. What one has to remember is that the data that comes from our instruments is the energy in the form of vibrations of different frequencies. To build a meaningful model from such a data set, besides the computer analysis what is essential is a specialist's judgement to differentiate between the various frequencies and identify critical features that help to arrive at the best possible model from amongst the many possible ones. While observing the vibrations created by nature and by manmade processes, an individual normally attributes the event to location-related phenomena, forgetting the intricate relationship between various factors responsible for such actions, including nonlinearity and non accessibility of the hidden parts of the Earth. To the quantum physicist it is an inseparable web of vibrating energy patterns in which no one component has reality, independent of the entirety; which includes the observer also. Thoughts and sensations are like search lights, only when these two mould into one are we in a position to logically analyse the event. This understanding helps in the progressive development of science in general, and the branch of "seismic imaging" in particular.

WHAT IS IMAGING AND SEISMIC IMAGING?

Imaging is normally defined as the process of replicating an object, using different tools and techniques. The resulting images may be multi-dimensional. Seismic imaging is a tool that bounces sound waves off underground rock structures to reveal the possible tectonic structures. This is of great importance to mineral and oil exploration as well as for addressing issues / problems associated with engineering, archaeology and geodynamics. One needs to generate quality data if one wants to create good quality images of the subsurface (imaged by acoustic waves) from raw experimental data. The data has not only the signal but also noise. The noise is of different types namely cultural noise, noise created by subsurface non linearity, improper recording geometry and instrumental limitations. It is of paramount importance to limit the effect of noise by enhancing the signal to noise ratio. In this exercise noise elimination is done through filtering techniques. Filtering is an important part of the exercise, and as such the observer and processing expert should use appropriate noise suppressing filters both at the time of acquiring and processing of seismic data.

The different types of geophysical imaging include 1) Electrical Resistivity Tomography, 2) Ground penetrating radar, 3) Induced polarization and 4) Seismic Tomography and Reflection seismology. In this summary only the last technique is discussed.

Seismologists use ultra sensitive devices called geophones to record the sound waves reflections from within the earth. The reflections produced by seismic soundings are processed by computers into images that reveal subsurface geology and structure. By studying the waves, experts calculate the depth of subsurface geologic formations and map the structures. Energy companies have been using seismic imaging for 80 to 90 years, and ongoing technological developments have provided high precision and effectiveness and thus added a new a dimension to efforts to locate favourable structures of importance. Waves exhibit marvellously complex geometrical patterns and much can be learned with simple mathematical analysis. But one should have familiarity with calculus, complex exponentials, and Fourier Transformation. However, it is essential to know the following to enhance the quality. Geometrical figures and objects are stationary in nature. Waves are dynamic in nature and change shapes according to the changes in the physical properties of the medium of transmission. Even the so-called "stationary wave" is the nomenclature given to the pattern set up by a dynamic wave train striking a reflector at a distance which is a multiple of half the wave length of the dynamic wave.

Basic principles governing the seismic wave propagation include its generation, transmission, absorption, and attenuation in the earth materials and its reflection, refraction, and diffraction characteristics at discontinuities.

There are two types of seismic images produced as the sound waves travel into the ground. Reflection and Refraction .Reflected waves travel down, bounce off a layer and return to the surface. Refracted waves are those which travel downward from their source along slant paths, approach the high speed layers at a critical angle and travel along their surface, and return to the surface along a critical- angle path rather than at normal incidence. Reflected waves generally show more subsurface details. The seismic method is based on whether or not a wave undergoes a reflection during its travel. Thus, while most refracted events are not reflected, most reflected events are refracted, because refraction occurs across any velocity interface in accordance with the simple and basic Snell's law. The seismic method is thus basically divided into Refraction and Reflection techniques. On the basis of theoretical studies it is known that the reflection coefficient of the reflected waves increases sharply beyond the critical angle .

The seismically reflected events from the earth's crust can therefore be divided into two groups a) sub-critical or near vertical reflections, and b) post critical or wide angle reflections (WAR) and the study of WAR adds a new dimension to seismic studies, particularly for crustal and upper mantle studies of a region. Seismic refraction and wide-angle reflection surveys are essential complements to the deep seismic reflection surveys which are deployed for crustal and upper mantle studies of a region.

Multiple "echoes" can make reflections very difficult to interpret. Seismic images have become more accurate with the development of more sophisticated velocity models, which contain information about the speed with which the seismic waves travel through the hidden rock strata. As such, coincident seismic reflection and refraction studies need to be given top priority, even if such an exercise is costly. To produce good quality results, the different aspects of various seismic imaging techniques need to be implemented through simulation. Sophisticated 3-D imaging creates high definition pictures of subsurface geology. The result is similar to an X-Ray or medical sonogram. The probable error in judgement/ diagnosis can be cross-checked by post-mortem in the case of medical imaging, but is often not possible in the case of the Earth (especially when one is imaging structures of deeper depth).

DEVELOPMENT OF REFRACTION AND REFLECTION SEISMICS AND SEISMIC IMAGING OF SHALLOW SUB SURFACE STRUCTURES

Geophysics involves the determination of various properties of the earth via the application of physical theories and measurement techniques. The sub discipline of applied geophysics covers a broad spectrum, ranging from earthquake prediction through engineering and environmental analyses and on to critical military issues such as detection of nuclear tests. However, the dominant role for applied geophysics over the past 80 years has been exploration and development of natural resources. All major theoretical components of classical physics can be adapted to geophysical exploration. World War I provided the impetus for the introduction of seismology to mineral exploration. Exploration geophysics can, arguably, be split into two parts- the initial era, which lasted from the 1920s until one generation past World War II, and the digital era, which began in the 1960s and continues to the present. The advent of 3-D seismics in the mid- to late 1980s helped to advance the development of computer workstations because the massive amount of the data collected in a 3-D survey simply could not efficiently be interpreted by old paper-based techniques.

Imaging of the basement configuration as well as the finer structures present below the basement require different strategies than imaging of deeper crustal layers. To image the basement configuration, we invariably require high precision, shallow probing devices. Scientists use shallow seismic refraction and shallow seismic reflection recording instruments. Since earthquake-generated waves usually originate from subsurface depths, and as there is some ambiguity associated with the focal depths of these natural vibrations, exploration geophysicists left out this field of seismology for exploration of mineral and oil resources. Significant strides have been made in the USA since the mid-nineteenth century to explore the Earth's interior using the combined knowledge of geology and geophysics. The earliest work in the field of seismology was carried on by Robert Mallet (1851), who had a surprisingly clear understanding of what could be accomplished by the use of artificial (active) seismic waves. One of the first practical applications of active seismic waves was through sonic depth finding and the use of reflected waves. Reginald Fessenden in 1914 used both reflected and refracted sound waves for locating mineral bodies. In the latter part of the nineteenth century, significant success was achieved in locating salt domes using artificial seismic waves. The practical use of seismic waves to explore shallower depths for minerals and oil took shape during the mid-nineteenth century. In his classical review on "History and development of seismic prospecting" B. B. Weatherbay8 (1948) gives a vivid account of the development of seismology since the nineteeth century. Some excerpts from that paper are included below, as the details are appropriate in developing this article.

''In 1851, Robert Mallet of the USA reported on the results of some field experiments in which velocities of artificial seismic waves were measured in granites and loose sand. He used a seismoscope for the experiment. The seismoscope consisted of a bowl of mercury from the surface of which was reflected a spot of light in the form of cross hairs. This spot was observed through a small telescope. When the surface of the mercury was agitated the image disappeared. Consequently the arrival of the wave was signified to the observer by the appearance of surface ripples that destroyed the image. The starting of a chronograph by the observer fired the shot electrically, and as soon as the wave appeared at the seismoscope the same observer stopped the chronograph. Thus the time of transit of wave was determined and since the distance between the shot and the seismoscope had been carefully measured, the velocity could be calculated. Due to low sensitivity of his seismoscope, Mallet could not measure the true longitudinal velocity of the materials. H.L. Abbot (1878) using energy from a 50,000 pound explosive measured the velocity of transmission of seismic waves. He set up several seismoscopes of the Mallet type in different azimuths and at varying distances. After realizing that the earliest arrivals of energy cannot create enough disturbance of the mercury surface to be detected, he increased the power of the telescope. He noticed an increase in the velocities. A few years later Milne and Gray conducted more elaborate experiments in Japan, using the impact of a falling weight to generate the waves. These were recorded on mechanical seismographs on moving smoked glass plates. Subsequently they used explosives as an energy source to study the nature of the vibrations. They also studied variations in amplitude with distance. Milne (1885) showed that different materials have different velocities. Fouque and Levy in 1889 made an improvement in the apparatus, by using a photographically recording seismoscope of higher sensitivity. Hecker in 1900 used both longitudinal and transverse components of seismographs along a line. This was indeed, a profile, as we know it today.

To the theoretical development of the method, Schmidt in 1888 pointed out that the wave velocity would increase with depth below the surface. Knott in 1899 wrote about the propagation of seismic waves and their refraction and reflection at elastic discontinuities. Belar in 1901 mentioned that sensitive instruments can be used to learn beforehand the composition of the Earth's crust, to better plan tunnel construction. He also stated that a series of tests carried out along a tunnel line on the surface would be sufficient to have a reliable knowledge of the elastic conditions of an earth stratum which would not be accessible by other means. By 1907 Wiechert and Zoepptitz worked out the theory of seismic wave transmission through the earth and gave solutions to the problems of seismic wave propagation, refraction and reflection. In 1910 Wiechert brought into light the importance of refraction.

Thus the early investigators had determined that artificial seismic waves generated by high explosives were analogous to the propagation of seismic waves generated by earthquakes. They built instruments to pick up the tremors, and to record and time them. They had developed an entirely adequate theory of wave propagation, which included profiling as a means of obtaining layer velocities and thicknesses. Lastly, they suggested practical uses of the method. The earliest studies were confined to measure the velocity of seismic waves. After the publication of Wiechert`s paper (1910) researchers realized the practical utility of seismic refraction methods. In 1914, Wilip pointed out that it had not previously been possible to accurately determine the hodograph (Travel Time curve) of seismic rays for shorter distances, and the top-most layers of the Earth. He stated, however, that the characteristics of the vibrations of the top-most layers of the earth's crust could be of great practical importance to mining operations.

Other practical applications of artificial seismic waves soon followed, including sonic depth finding, and the use of "reflected waves." Reginald Fessenden in 1914 applied for a patent covering both refracted and reflected sound waves. From the time of transit of the wave it was possible to tell whether it had suffered any unusual deviation. The Geophysical Research Corporation of Kracher strived to develop an improved reflection seismograph. It was found necessary to drastically modify the refraction apparatus to obtain satisfactory reflection records. For refraction work, the whole system was designed to pass low frequencies to record first arrivals. Such a system was undesirable for reflection work. To filter out low frequency ground wave and other low frequency noise electrical filters were introduced. In practical applications, the pioneering work of J.J. Jakosky (1938) in applying seismic reflection technique with linear strings of multisensors for petroleum exploration assumes importance. M.M. Slotnick (1950) developed a graphical method of interpreting refraction profiles to overcome the then cumbersome processing procedures. He presented by means of a complete solution of a numerical example, geometrical methods of mapping subsurface refracting layers.

After the First World War, Mintrop in 1919 applied for a patent in Germany covering the use of refraction profiling for locating the depth and type of subsurface formations. Credit for the successful use of refraction fans (multiple refraction lines set up in a fan shape) goes to L.P. Garrett. The Geophysical Research Corporation headed by J.C. Kracher was responsible for designing entirely new recording equipment in 1925-26. The newly designed electrical detectors and amplifiers were many times more sensitive than the mechanical seismographs. Radio communication between shot point and detector permitted radio transmission of the instant of explosion, allowing greater accuracy in timing. Distances between shot and detector were found by using the airwaves. The above advantages increased the speed of shooting, which led to cost reductions. As a result of these improvements, dozens of salt domes were discovered in the swampy coasts of Louisiana, USA. During exploration of the Gulf coast of Texas and Louisiana, refraction profiles were shot to give an idea of the form of the time distance curve.

In refraction work, a party used two or three recording trucks, each with one complete recording unit consisting of a detector, amplifier and camera. Early in the development of reflection seismology the multiple element camera, or oscillograph, was introduced with which four to six complete recording channels could be used. The introduction of such a multiple element camera aided in better resolving the recording of reflections, including minute character changes. In the late 1930s and 40s, substantial improvements were made both in apparatus and technique, resulting in increased stability of the equipment used. "Automatic gain controlled amplifiers" or "Amplifiers with automatic limiting of the amplification range" have helped in making the early part of the record compressed and readable. Narrow band filters have helped to eliminate extraneous energy from the record. Changes in technique include the use of multiple geophones and in much closer spacing of data. Continuous profiling helped to better correlation of seismic phases. Improved imaging of the structure of sedimentary basins proved to be a boon to the oil industry from the 1930s onwards.

Developments in data acquisition and processing

After the Second World War significant strides have been made in data acquisition and processing. Since presentation of these developments would make the manuscript un wieldy, only some specific developments are detailed below. I regret for such a sketchy presentation of important developments. Multichannel recording has enhanced phase correlation. In reflection and refraction surveys new recording geometries were introduced. Point profiling, skip profiling, broad side shooting, crooked line profiling and processing these different sets of data through specially generated processing techniques helped in covering logistically complicated regions. Common Depth Point(CDP) technique in reflection recording has brought out clarity in imaging of different structures. Digital recording has enabled signal enhancement and easier way of acquiring and processing reflection and refraction data. Digital records enabled use of both time and amplitude of seismic waves and helped in producing kinematic and dynamic modelling. Synthetic seismograms brought out better correlation between observed data and generated models. The enhanced communication through radio frequency telemetry enabled better coverage of logistically in accessible zones. Introduction of noise suppressing filtering, both at the time of acquiring and processing data, helped in producing better stack sections. Time variant filters segregated clearly different horizons and enhanced quality in reflectivity.Supression and elimination of artefacts , multiples through specialised processing techniques and production of dipping horizons through migration techniques helped in better imaging of subduction zones , sutures and shear zones.

Pre stack depth migration techniques have helped in producing deeper structural images from individual shot gathers. Enhanced signal processing and full wave form modelling helped in better utilisation of acquired data. Introduction of 3-D reflection has enhanced quality of images, as structural resolution could be enhanced significantly, compared to 2-D recording. Introduction of three component stand alone systems has helped in acquiring both P- and S-wave data simultaneously. Passive seismic data was obtained, during 1960-1980, using worldwide seismological station net works(both short and long period data). Broad band seismological stations and portable seismological stations, strong motion data gathering instruments, GPS data gathering surveillance net works have helped passive seismologists in gathering valuable data.

SEISMIC IMAGING OF THE CRUST

Let us now look into the historical development of modern seismic imaging of the crust, during the past 50 to 60 years. After the second World War, scientific research using controlled source refraction and reflection seismology began with renewed vigor. This resurgence was driven mainly by the desire for identification of the deeper structure of the Earth. After the first recordings of seismic normal-incidence reflections from the crystalline crust and the Moho by the use of chemical explosions as a seismic source (especially in Western Europe), rapid progress was made in imaging the structure of the whole crust. This progress followed earlier development of the controlled source methods based on registration of seismic refraction and wide-angle reflections, especially in the Soviet Union and eastern European countries. The international Upper Mantle Project (UMP) of 1960 to 1970 marked a strong increase in the application of controlled source seismological techniques throughout the globe, and led to the first experiments that aimed at imaging the mantle by wide-angle techniques.

The two biggest experiments at this time were the Early Rise experiment across most of North America (collaboration between US and Canadian institutions) and the Soviet Peaceful Nuclear Explosion program (the largest controlled source seismological experiment ever conducted) that took place between 1965 and 1968. These studies revolutionized the field of seismic imaging. The Early Rise experiment consisted of twelve profiles radiating from a common point in Lake Superior to generate single-sided seismic data to image not only the crust but also the subcrustal lithosphere and the transition zone. Stimulated by these experiments, several seismic expeditions using offshore shots were also undertaken by Japan. The Soviet experiment included 41 nuclear detonations, and generated dense arrays of seismograms to offsets of 4000 km.These experiments were part of a sweeping change in geophysics as a science. While controlled source seismological studies got impetus, the conventional earthquake seismologists continued to image the deeper columns of the crust using body wave travel times and dispersion of surface waves. The results from both the active and passive seismic sources complimented each other and resolved many problems associated with the thickness and shape of different sub surface layers and the velocity within them.

In the 1960s, magnetic stripes were found on the ocean floors that seemed to match on either side of the oceanic ridges. This was the first step in the development of plate tectonic theory which would ever-after change geophysics and consequently how scientists viewed seismology. The earlier results from seismic imaging of continental and oceanic crust are both informative and significant. Some of the results are listed below

Andrija Mohorovicic discovered the continental crust from studies of the seismic waves generated by the Croatia earthquake of 1909. The first seismic arrivals were P waves that traveled directly from the focus to the recorders with a velocity of 5.6 km/s. This seismic phase was termed Pg. At greater ranges P waves with a much higher velocity of 7.9 km/s became the first arrivals, termed the Pn phase. These data were interpreted by the standard techniques of refraction seismology, with Pn representing the seismic waves that had been critically refracted at a velocity discontinuity at a depth of 54 km. This was subsequently named as the Mohorovicic discontinuity, or Moho. Continental crust is on average 40 km thick but thins to less than 20 km beneath some tectonically active rifts and thickens up to 80 km beneath young orogenic belts (Christensen & Mooney, 1995; Mooney et al, 1998). Victor Conrad confirmed the discontinuity within the continental crust in 1925, using similar methods. As well as the phases Pg and Pn, he also noted an additional phase P* which he interpreted as the critically refracted arrival from an interface where the velocity increased from 5.6 km/s to 6.3 km/s. This interface was subsequently named the Conrad discontinuity. Conrad`s model was readily adopted by early petrologists who believed that two layers were necessarily present in the continental crust. The upper layer, rich in silicon and aluminum, was called the SIAL and was believed to be the source of granitic magmas, while the lower, silicon-and magnesium-rich layer or SIMA was believed to be the source of basaltic magmas. It is now known, however, that the upper crust has a composition that is more mafic than granite, and that the majority of basaltic magmas originate in the mantle.

Anisotropy plays an important role in understanding the structure and composition of subsurface structures. Processes in the deeper crust play an important role in continental deformation, and whether new structures are created or pre-existing ones are rearranged, these processes produce features that can be revealed by seismic waves. In all tectonic regimes, ductile flow or deep shear zones in the middle to lower crust are thought to accommodate brittle faulting in the upper crust. Numerical models support the idea that crustal flow must occur during the formation of high continental plateaus, as well as during their collapse. Petrological studies highlight a range of large-scale mixing processes between the crust and mantle—including foundering of the lower crust and underplating of subducted continental margins—that may play major roles in the evolution of the crust. Despite the widespread acceptance of these ideas, many details of the relationship between crustal deformation processes and its seismic imprints remain unclear. This situation can be attributed to a number of factors, including the heterogeneity of the crust, the poorly constrained rheology, the rarity of lower crustal seismicity, the difficulty of imaging the lower crust, and the scarcity of surface exposures of the lower crust. Recent developments in seismic imaging of crustal anisotropy hold promise to improve this problem. A diverse set of seismic waves exist that can offer unique imaging of subsurface anisotropy. These waves differ by source (earthquakes, explosions), vertical/ horizontal ray path (local, regional, teleseismic earthquakes), resolving ability (0.1 to several km), and phases (P-, S-, and converted-body waves, and surface waves). A major hindrance in this effort, however, remains our incomplete understanding of the possible causes, scales, and relationships of structural fabrics to seismic anisotropy in the crust. Clearer communications among seismologists, mineral physicists, and structural and metamorphic geologists will be required to advance this effort. (Zandt et.al,2009)

The oceanic crust is in isostatic equilibrium with the continental crust according to the Airy mechanism, and is consequently much thinner. Seismic refraction studies have confirmed this and show that oceanic crust is typically 6-7 km thick beneath an average water depth of 4.5 km. Thicker oceanic crust occurs where the magma supply rate is anomalously higher than normal temperatures in the upper mantle. Conversely, thinner than normal crust forms where upper mantle temperatures are anomalously low. A typical oceanic crust has three layers below the water column. These are: a 0.4 km thick (average) first layer of P- wave velocity of 1.6-2.5 km/s, a second layer of 1.4 km thickness (average) with a P- wave velocity of 3.4-6.2 km/s, and a third layer of about 5 km average thickness with a P- wave velocity of 6.4-7.0 km/s. The Moho boundary (typically with a Pn velocity of 7.4-8.6 km/s) lies at an average depth of 6 to 7 km below the water layer (Kearey et al, 2009).Academic research using marine multichannel seismic (MCS) methods to investigate processes related to Earth's oceanic crust has made substantial advances in the last decade (Canales etal, 2012). These advances were made possible by access to state-of-the-art MCS acquisition systems, and by development of data processing and modeling techniques that specifically deal with the particularities of oceanic crustal structure and the challenges of subseafloor imaging in the deep ocean. Among these methods, multistreamer three-dimensional (3D) imaging, streamer refraction tomography, synthetic ocean bottom experiments (SOBE), and time-lapse (4D) studies assume importance.

Methods for imaging of the crustal structure developed rapidly during 1970s and 80s with the establishment of national research groups to apply the new normal-incidence techniques, including for example, COCORP, BIRPS, DEKORP, ECORS and LITHOPROBE. These programs provided spectacular images of significant structures in the crystalline crust, which could be related to, in particular, low angle fault zones and characteristic reflectivity from the lower crust. Also established during these formative years were global seismic networks capable of conducting passive experiments. The U.S. Geological Survey and U.S. National Science Foundation provided funding in 1984 to create a digital network (the Global Seismic Network (GSN)) that would conduct research on earthquakes and crustal structure. This was the first time a digital network was deployed at such scale.

In the 1990s, the International Data Center was established in Vienna, Austria to use the GSN stations for further research, but also to monitor clandestine nuclear tests around the world as a method of enforcing the Comprehensive Nuclear Test Ban Treaty. Today, monitoring is still done through the International Monitoring System (IMS) in Austria.

SEISMIC IMAGING OF LITHOSPHERE:

To better understand the inter relationship between lithosphere dynamics and surface manifestations resulting from deep seated phenomena, imaging of lithosphere has assumed importance. During 1960s nuclear explosion resultant energy was utilised by US scientists to delineate internal structure of the earth to depths beyond 1000Km.At the same time European, specially the British and German scientists have delineated upper mantle structure, using body wave travel time data from nuclear explosions. Free oscillations recorded after high magnitude earthquakes have been utilised to generate deeper velocity models. American, west and east European seismologists have clearly imaged asthenosphere-lithosphere boundary, Lehmen`s discontinuity, 400 and 600 km discontinuities.

Seismic tomography , introduced in 1970s, has significantly helped passive seismologists in delineating sub Moho upper mantle structure, including topography and varied characteristics of different discontinuities present in the upper mantle. Significant results emerged from tomographic investigations in US , leading to initiation of similar studies in different parts of the world. Seismic tomography is a technique for imaging Earth's sub-surface characteristics in an effort to understand deep geologic structure. Gathering ample compressional wave (P-wave) and shear wave (S-wave) travel time measurements allows us to compile 3D images of

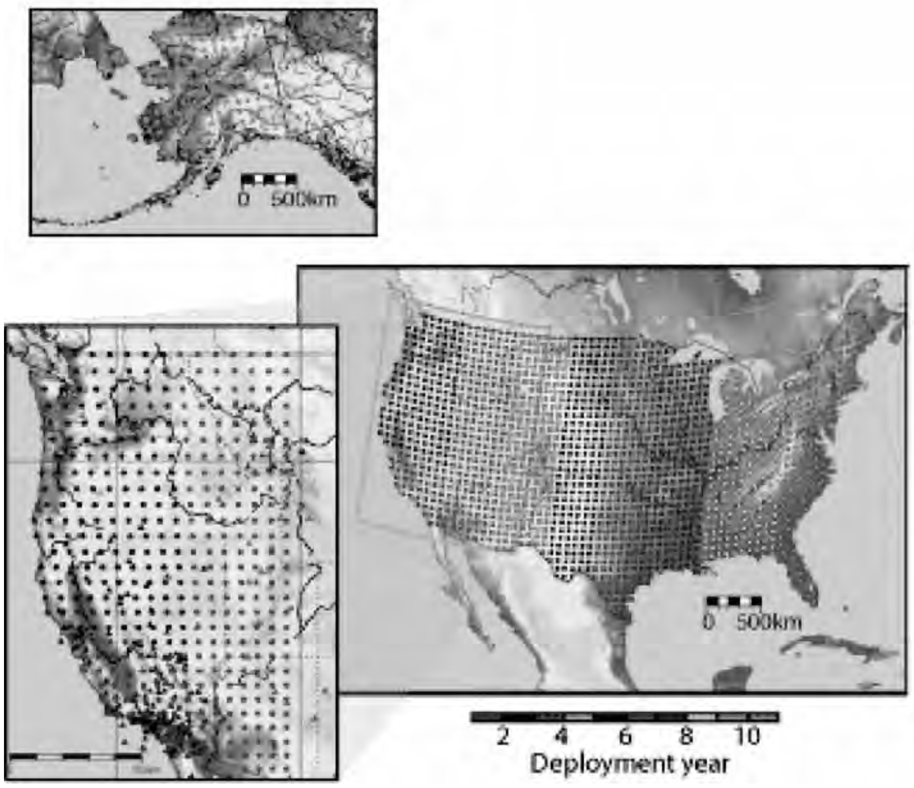

Figure 2. Earthscope's USArray deployment. This passive experiment consisted of: 400 portable three-component broadband instruments on a regular grid, 400 portable three-component short-period and broadband seismographs and 2000 single channel high-frequency recorders, and a permanent array of broadband three-component stations across the U.S. as part of the USGS Advanced National Seismic System (courtesy of Earthscope).

earth's velocity structure. Since this technique has assumed importance in imaging deeper crustal and sub crustal lithospheric structures let us know the basic principle associated with this technique.

Tomography is solved as an inverse problem. First measurements are made of seismic waves passing through a material. The character of these measurements is then analyzed to make inferences on the material such waves have passed through (velocity, density, etc.). The velocity of P and S waves depends on the rheology of the material that they travel through (density and elasticity). In short, variations in chemical compositions and thermal structure result in a change of velocity. Such waves can travel faster through relatively colder material. It is observed that wave velocity increases with increasing depth from 2–8 km/s in the crust and up to 13 km/s in the mantle. Current research is based on this premise. A compilation of arrival times, sometimes millions of data, allows seismologists to have a clearer picture of the location and size of sub-surface structures. The result is a 3D image of a slice through the earth that serves as a seismic velocity map. The image depicts where seismic waves were able to travel faster or slower based on the differing arrive times of the waves. This in turn warrants the interpretation of the thermal structure for the deep Earth.As stated above, seismic tomography is typically solved as an inverse problem. In order to estimate P-wave velocity and further simplify seismic tomography, four main methods have been devised:

- Refraction traveltime tomography:
- Finite-frequency traveltime tomography:
- Reflection traveltime tomography
- Waveform tomography :

Seismologists can use tomography to infer geologic structures such as the subduction of tectonic plates into the warmer mantle or the rise of a relatively hot plume body. Volcanologists use tomography to understand the scale of magma chambers beneath volcanoes. The study has also allowed for the correlation of tomographic observations with fluid dynamics models by providing a view of the internal thermal structure of the mantle.Like many fields in geology there exists many limitations and unanswered questions in seismic tomography. For example, it provides only the current velocity anomalies, similar to conventional refraction technique. We cannot see how the velocity structure has changed over earth's history. It is also difficult to image slender structures due to the fact that long-wavelengths are easier to recover in such a survey.

Receiver function is a popular method for studying crustal and sub crustal lithospheric structures near seismic stations. The conventional method of constructing receiver functions requires all three components of data. Signals on the vertical component are assumed to mainly represent effects near the earthquake source and are removed from the horizontal components by deconvolution. The result emphasizes P-to-S conversion across the Moho and deeper discontinuities and related multiples. However, this procedure also removes important information from the P- wave field, which is mainly recorded on the vertical component. Both the teleseismic tomography and teleseismic receiver function techniques, have added quality to lithospheric imaging(courtesy GOOGLE search).

Passive experiments continued into the new millennium as continent-wide projects were now getting underway. For example, the USArray component of the EarthScope experiment is a continental-scale seismic observatory designed to provide a foundation for integrated studies of continental lithosphere and deep Earth structure over a wide range of scales. USArray (still underway) is already providing researchers with new data to address fundamental questions in earthquake physics, volcanic processes, core-mantle interactions, active deformation and tectonics, continental structure and evolution, geodynamics, and crustal fluids (magmatic, hydrothermal, and meteoric). The USArray facility consists of three major seismic components (Fig 2):

1. A transportable array of 400 portable, unmanned three-component broadband seismometers deployed on a uniform grid that will systematically cover the US;

2. A flexible component of 400 portable, three-component, short-period and broadband seismographs and 2000 single-channel high frequency recorders for active and passive source studies that will augment the transportable array, permitting a range of specific targets to be addressed in a focused manner; and

3. A permanent array of high-quality, three-component seismic stations, coordinated as part of the US Geological Survey's Advanced National Seismic System (ANSS), to provide a reference array spanning the contiguous United States and Alaska.

Significant studies have been carried out through European Array.In broad the out come of these studies has revolutionized our understanding of geodynamic processes .Some important results are listed below.

During the past decade, the analysis and understanding of dynamic crust-mantle processes has greatly progressed owing to major advances in the field of seismic tomography at global and regional scales . Tomographic imaging techniques are applied to observations of body and surface waves, and provide spectacular 3-D images of mantle structures. These images can readily be linked to global plate tectonic processes, such as past and active subduction of lithospheric plates . Tomographic evidence for mantle plumes originating at great depth suggests links between mantle plumes and such surface processes as intra-plate volcanism, rifting and vertical surface motions.

For the European-Mediterranean domain, recently developed tomographic models of mantle structure have greatly advanced the linking of lithosphere-mantle processes to the past and on-going tectonic evolution of the Earth's crust . Conceptual models of mantle dynamics derived from tomography and analog lab-models emphasize the role of a variety of mantle processes as driving mechanisms of major tectonic processes, the mechanical evolution of the lithosphere, and surface deformations .

A very important part of a new generation of structural crust and mantle models are the discontinuities in material properties that occur around the crust-mantle interface (the Moho; a compositional transition as well as the granulite-eclogite transition), around 410 km depth (dominated by the olivine to β-spinel transition) and around 660 km depth (dominated by the γ-spinel to lower-mantle-oxides transition). Special seismological techniques can be used, and developed, to detect the topography and sharpness of these (and related) phase transitions, the precise nature of which is still a matter of active research. Receiver Function analysis of seismic data has proved to be a powerful method for the detection of the phase transition interfaces . The topographic configuration of these discontinuities is in fact dynamic, owing to the interaction of mantle flow (slabs, plumes) impinging on these interfaces with the physics of phase transitions. Dynamic surface topography is strongly diagnostic for the type and local nature and thermal characteristics of mantle flow. In long-wavelength mantle flow models, the dynamic surface topography is related to the dynamic topography of the internal surfaces. One of the key problems in understanding surface topography is the interaction between the mantle induced dynamic

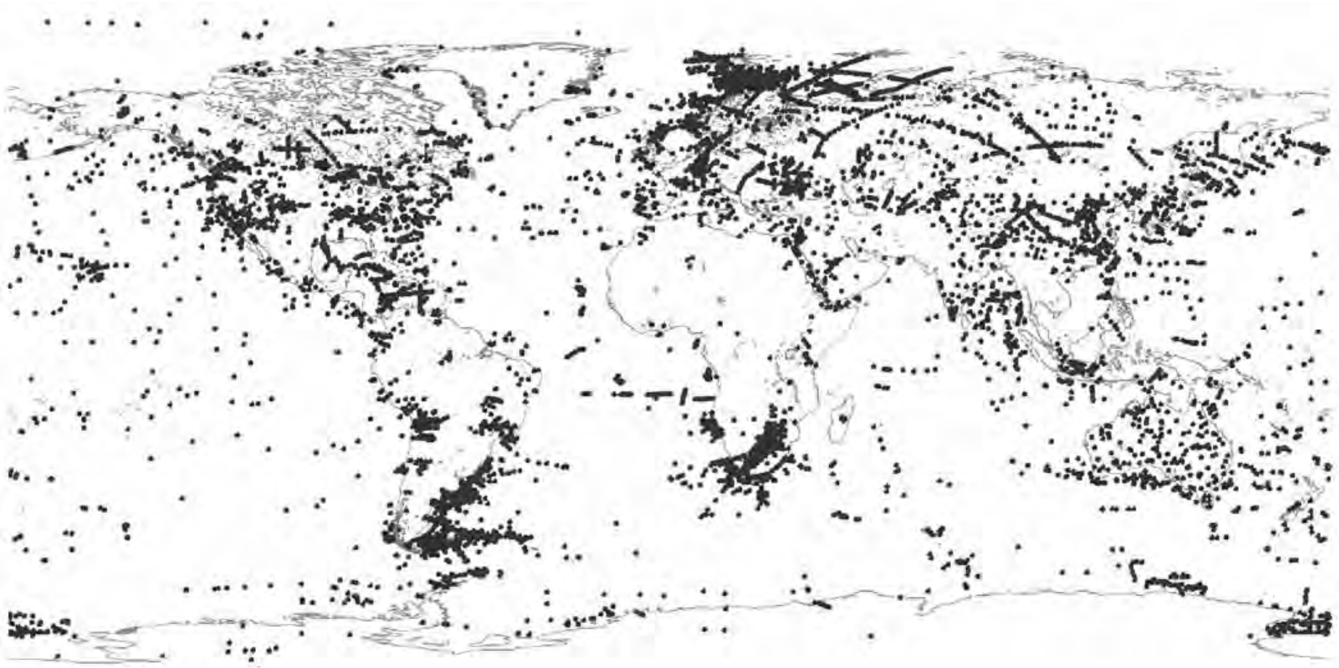

Figure 3. Map showing a partial representation of active and passive seismic experiments across the globe since 1930. The long "arcs" that sweep across Russia are the Peaceful Nuclear Explosions (courtesy USGS and Walter Mooney).

topography and other (shallow) topography generating processes(courtesy...EUROARRAY)..

New-generation models of the crust-mantle system can only result from a concerted effort of seismic tomography research, strong seismic-contrast and dynamic-topography research, and fine-scale imaging of crustal and mantle properties. providing an open data policy.The existing international seismic network, complemented by a growing US and EUROARRAYS of two independant co-located instruments, combined with existing state-of-the-art analysis and new seismological very high resolution modelling techniques, will reveal the internal structure of lithosphere and sub-lithospheric mantle with unprecedented detail. This will permit to develop advanced tomographic models for the lithosphere and mantle of important segments of the earth, greatly improving on presently available models:

- Determination of the detailed crustal structure beneath each station will lead to a high-resolution crustal model
- Mantle heterogeneities will be revealed at scales exceeding the traditional resolution limit and with a much-improved, uniform spatial resolution
- Dynamic topography of seismic discontinuities and the thickness of transition zones will be accurately and uniformly determined, allowing for the explicit detection of vertical mantle flow and associated temperatures
- The lithosphere-asthenosphere boundary, lateral variations in lithospheric structure, and large lithospheric shear zones on which deformation concentrates, can be detected
- Subducted lithospheric slabs, mantle plumes, and their relation to crustal structure and major continental deformation zones can be delineated in detail
- Uniform sampling of the mantle permits detection of seismically anisotropic structures, which will in turn allow distinguishing between deeper mantle flow directions and anisotropy frozen in the lithospheric mantle.

Apart from its own merits, a new-generation model of crustal and mantle structure will provide the necessary input for advanced modelling of the crust-mantle system constrained by high-resolution satellite gravity and geodetic observations of active surface deformation. This provides the "depth-to-surface" relations required for the reconstruction of mantle induced surface topography. The current generation of tomographic models can and will, within limitations, be exploited for this purpose during the early phases of TOPO-EUROPE and TOPO-US and for the development of 4-D modelling techniques of crust-mantle dynamics. This will work out well for some selected regions where current tomographic resolution is relatively high (e.g. Apennines-Aegean-Anatolia of Europe and different segments of US), but will lead to ambiguous results for Western, Central and Northern Europe and other parts of the world(including the Himalayan belt, seismically active Sumatra-Andaman segment of Indian plate, circum Pacific belt)where the spatial resolution is much lower. In parallel, US and EUROARRAYS will focus on developing the Earth observation data-platform required for near-future Solid-Earth science and topography research.

Inspite of these successes, we need to enhance our knowledge base by covering other parts of the earth with dense station net works/Arrays, as whole earth models can alone address better ,important unresolved problems.

It is good to learn that Africa Array has also begun, and plans are being considered for an Asian Array, with many agencies and countries wishing to participate. Across the globe, our understanding of the Earth's fundamental processes is being greatly enhanced through the use of well-planned seismic experiments (both active and passive; Fig 3). These developments are helpful in addressing many important questions related to structure and dynamics of different crustal and sub crustal lithospheric segments.However, we are yet to understand unequivocally, the mechanism of stress genesis, build up, transfer and release and knowledge about strain along and across active seismic zones.This knowledge is paramount to take a significant step forward in predicting inter and intra plate seismicity.It is essential for us to enhance our surveillance net work(including establishment of closely spaced Arrays) and carry out continuous GPS investigations, to understand various mechanisms that are time and space variant.Real time precision imaging of sub surface structures can provide important clues to strengthen our knowledge base.We need to co-operate with each other in strengthening our knowledge base, by exchanging useful data, to solve this globally important issue that is hampering our disaster management programs.

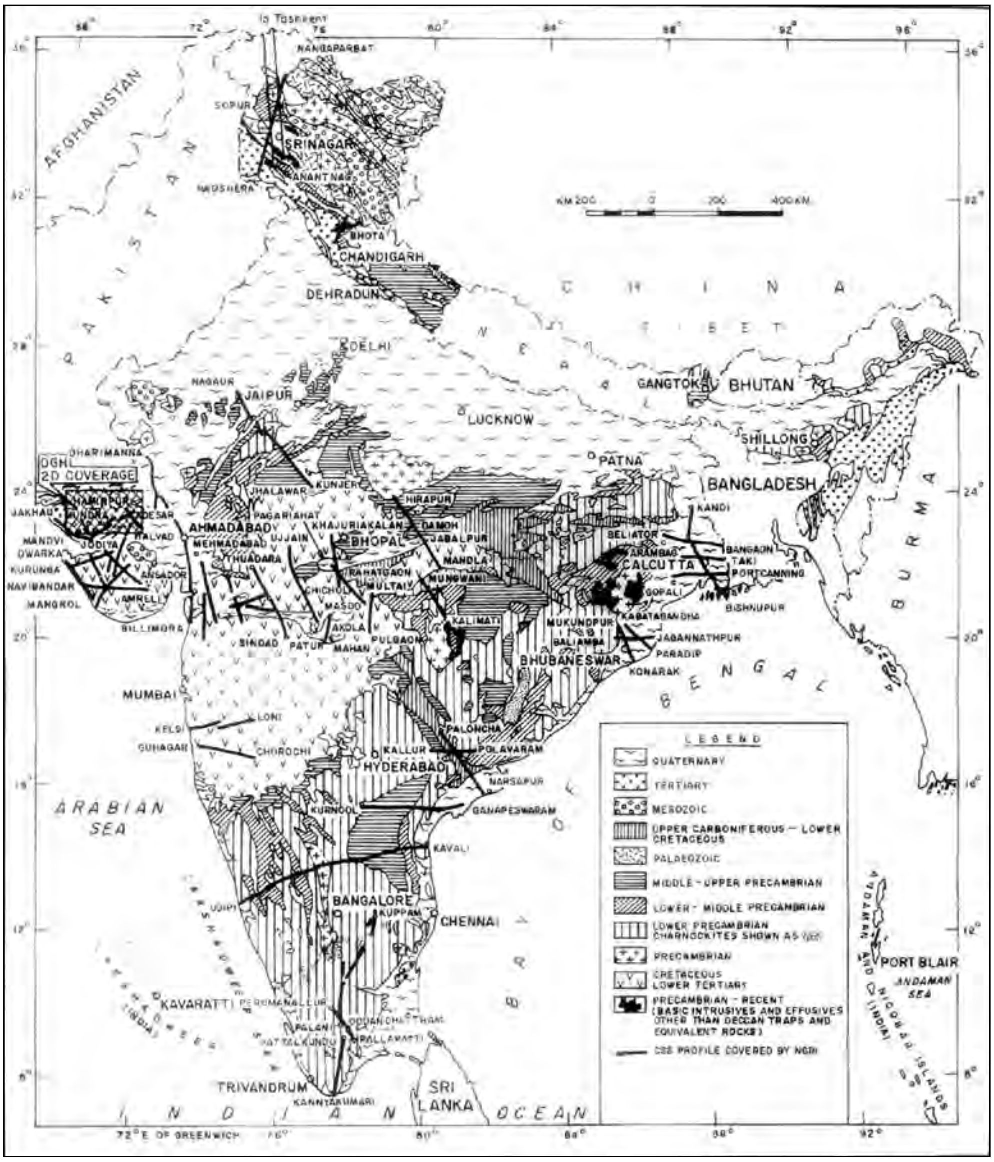

Figure 4. Controlled Source Seismic Profiles in India, 1972-2009

STUDIES IN INDIA:

Prior to the development of Instrumental seismology, the first scientific study of an Indian earthquake (The Great Cachar earthquake of 1869) was initiated by T. Oldham of Geological survey of India (GSI).His son R.D. Oldham made a thorough study of the Great Assam earthquake of 1897 and recognized the existence of the P-, S-, and Surface waves on the seismogram. After this, a significant number of seismological stations were established and crustal seismic studies were initiated from 1930s onwards. In addition to these passive seismic investigations, active seismic experiments were carried out in the first half of 20th century along select profiles in Assam by Stanvac and Burmah Shell companies .These studies were followed by intensive seismic investigations by Indian oil industry, post independence, across different sedimentary basins. Significant passive seismic studies, using body wave travel time data and surface wave dispersion data, were carried out(1945-1980) to delineate crustal structure of Himalayas, Indo-Gangetic plains, Peninsular shield and parts of the Arabian sea and Bay of Bengal.India Meteorological Department (IMD) and NGRI scientists contributed significantly to these investigations.Using deep earthquake travel time data and indigenously developed analytical processing technique,NGRI scientists have delineated deeper velocity inhomogeneities present below Hindukush, Burmese arc, Japan, Kurile islands and other segments of the earth (where intermediate and deep focus earthquakes occur).These studies have clearly established the presence of 400 and 600/ 650 km discontinuities.Using shallow seismic body wave travel time data and travel time curve splitting technique,lateral and vertical velocity inhomogeneities present upto depths of about 800 km in different directions from central part of Indian continent have been delineated at NGRI.Both these studies were carried out during 1965 to 1980. From mid 1980s seismic tomography studies have been carried out covering many important geologic and tectonic segments of Indian continent.Since the last 15 years receiver function investigations have been carried out to better understand the structural variations present at different depths, extending beyond 600 km.Due to generation of shear wave velocity models, in addition to primary wave velocity information, these studies provided significant inputs to understand lithosphere dynamics, including the role of partial melts and volatiles in tectonically important segments of the Indian lithosphere. Studies to map subduction zones, collision fronts , mobile belts and cratons have received international recognition.These studies have been mainly carried out by NGRI scientists. Active seismic investigations for imaging deeper columns of the crust were initiated from 1972, as a collaborative scientific study with erstwhile USSR. During 1970s, 80s, 90s and in the first decade of 21st century significant passive and active seismic investigations have been carried out by Indian scientific organisations and Indian oil and mineral explortion industries. The Deep reflection profiling and Deep seismic Refraction studies carried out on land by NGRI have received accolades from one and all. NGRI`s efforts have solved/ addressed many fundamental problems associated with the mighty Himalayas, Aravalli-Delhi Fold Belt, Narmada-Son lineament,Central Indian Shear zone, different sedimentary basins, Kutch main land, Deccan Syneclise, Saurashtra Peninsula, Dharwar craton, Eastern Ghat mobile belt and Southern Granulite terrain. A coverage map is included, as a reference (Fig.4).

NIO has carried out significant studies covering Bay of Bengal, Arabian Sea and Indian Ocean and imaged systematically both the eastern and western continental margins in addition to mid oceanic ridges present in the Indian ocean. NGRI and NIO efforts, with support from the oil industry, have ensured that we can achieve energy security to a considerable extent by exploring and exploiting Gas Hydrates.For specific results readers are requested to refer the book of P.R.Reddy, published in 2010. Presently advanced 3-D investigations for imaging shallower structures and comprehensive standalone and multichannel based deeper investigations using state of the art technology are being carried out.

CONCLUSIONS:

In conclusion, it is hoped that the above details give a reasonably comprehensive exposition of seismic imagining techniques. While developing this article I have kept in mind the chronological development of various methods starting from early 19th century. While I feel the details are generally exhaustive, I recommend those who are interested to refer to special publications on seismic methods, since the seismic technique has developed by leaps and bounds over the past several decades. Another factor that has to be kept in mind is that the processing methodologies developed during this period to interpret shallow seismic 2-D and 3-D oil exploration data have yet to be used to process deep seismic reflection data, due to inherent depth related problems. As such we have more progress to make before generating near-error-free models that can effectively image the clear structural and compositional complexities associated with deeper crustal columns and sub crustal lithosphere.

Instruments and methodologies evolve with time. Knowledge of this evolutionary process is important to understand the merits and limitations of the results/models generated using these instruments and methodologies. In using "state of the art" techniques to bring out quality images, it is necessary to know how "unique" the models are. It is essential to know that the "Earth" is dynamic and its structure and evolution changes with space and time. As such no technique can bring out images that can be called truly "unique." Thus, our efforts should be aimed only at producing acceptable models that can stand up to present day quality control. The models we produce today may become obsolete in the future, along with the data acquisition and processing instruments and methodologies. This truth needs to be kept in mind by each and every researcher. However, we need to strive continuously to enhance the quality of the tools and the generated results.

ACKNOWLEDGEMENTS:

I am thankful to Mr. Shane T. Detweiler ,USGS for valuable inputs. Ms. T.Sirisha lent her assistance in preparing this manuscript. I am thankful to editorial team of journal of IGU for inviting me to write a review article, on "seismic imaging".

REFERENCES:

Abbot, H.L., 1878: "On the velocity of Transmission of Earth Waves"- American Journal of Science and Arts, series 3, New Haven, Connecticut. 15, 178-184.

Belar ., 1901: Ref: Weatherbay, B.B, paper., v.1, Geophysical Case Histories, 1948, Edited by Nettleton, L.L.

Cagniard, L., 1958: Reflection and Refraction of Progressive Seismic Waves. , McGraw-Hill, New York .

Canales, J.P., H. Carton, J.C. Mutter, A. Harding, S.M. Carbotte, and M.R. Nedimović. 2012. Recent advances in multichannel seismic imaging for academic research in deep oceanic environments. Oceanography 25(1):113–115.

Christensen, N.I. and W.D. Mooney.,1995: Seismic velocity structure and composition of the continental crust: A global view., J. Geophys. Res., 100, 9761-9788.

Fouque, F. and Michel Levy., 1889: "Experiences Sur La Vitesse de Propagation des Secousses"- Memoires presentes par divers savants de l' Institute de France., Number 2, 30,57-77.

Fresnel A., 1818: Lettre de M. Fresnel à M. Arago, sur l'influence du movement terrestre dans quelque phénomenes d' optique. Ann. de Chimie et Physique. 9,57.

Hecker, O., 1900: "Ergebnisse der Messung von Bodenbewegungen bei einer Sprengung"- Gerland's Beitrage Zur Geophysik., IV, 98-104.

Huygens.Ch., 1690 : Courtesy Wikipedia.

Jakosky, J. J., 1938: Exploration Geophysics.

John Milne., 1885: "Seismic Experiments"-Transactions of Seismological Society of Japan,Yokohama., 8,1-82.

Kearey, P., Klepies, K.A. and Vine, F.J.,2009: Global Tectonics.,Wiley-Blackwell publication, 1-482.

Knott, C. G., 1899: Phil. Mag., Ser. 5, 48, 64.

Kuo.C.L, J.D.Huba, G.JOYCE and L.C.Lee,2011,Jou. Geophy.Res,116,A 1031,doi 10.1029/2011,JA 016628

Reddy,P.R., 2010: Historical Development of Passive and Active Crustal Seismic Imaging Techniques. In: Seismic imaging of the Indian continental and oceanic crust by P.R.Reddy. Published by Professional Books Publisher, Hyderabad, India.,1-475.

Reginald Fessenden., 1914: Ref. Weatherbay,B.B., paper, v.1, Geophysical case histories, 1948. Edited by Nettleton, L.L.

Robert Mallet., 1851: "Second Report on the Facts of Earthquake Phenomena"- British Association for the Advancement of Science.,21,272-320.

Schmidt, A., 1888: "Ein Beitrag zur Dynamik der Erdbeben"- Jahrenshefte des Vereins fur Vaterlandische Naturkunde in Wurttemberg, Stuttgart., 44, 248-270.

Slotnick, M. M., 1950. Geophysics, xv, 2.

Weatherbay, B.B., 1948: Geophysical case Histories, Edited by Nettleton, L.L., 1 , 7-20.

Wiechert,E. and Zoeppritz,K ., 1907: "Uber Erbdebenwellen"- Nachrichten von der konig-lichen Gesellschaft der Wissenschaften zur Gottingen., 415-549.

Wiechert, E., 1910: "Bestimmung des Wages der Erdbebenwellen im Erdinnern"-Physikalische Zeitschrift., 11, 294-311.

Wilip, J., 1914: "On an Artificial Earthquake Recorded at Pulkovo"- Proceedings of Permanent Central Seismic Commission., Number 2, IV,173-184.

Mintrop., 1919: Ref: Weatherbay,B.B., paper, Vol-1 Geophysical case histories, 1948. Edited by L.L. Nettleton.

Mooney, W.D., Laske, G. and Masters, G.,1998: CRUST 5.1: A global crustal model at 5° x 5°, J. Geophys. Res. 103, 727-747.

Wang Chen-To., 1936: The Severity of an Earthquake , a U. S. Geological Survey General Interest Publication. U.S. Gov printing office, 1989-288-913.

Zandt, George, Porter, Ryan C., and Okaya, David,2009. Imaging of Crustal Seismic Anisotropy: How we measure it and what does it mean? Abstract)Portland GSA Annual Meeting (18-21 October 2009)