The Indian lithosphere and asthenosphere

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Our understanding of tectonic processes and earthquakes depends on knowledge of the earth's crust and mantle and of inhomogeneities in the structure of these two layers. Analysis of seismic-wave velocities and travel paths allows modelling of the structure of the mantle. Seismic tomography, like its medical counterpart, provides three-dimensional models. Such analysis and modelling are required for the geodynamically interesting Indian region.

SINCE the development of the plate-tectonics hypothesis during the late sixties, it has been possible to redivide the crust–mantle domain of the earth's interior into three major layers of different thicknesses. The topmost layer, known as lithosphere or tectosphere, is 100 km thick, and overlies the asthenosphere of several hundred kilometres in thickness. The asthenosphere is a comparatively weaker zone. The remaining part of the upper mantle, below 700 km depth, and the lower mantle have been classified as mesosphere[1]. It is now well known that the outer layer of the earth, i.e. the lithosphere, consists of a dozen rigid, crust-bearing plates that ride on the underlying mantle, rearranging continents, forming mountains, creating and destroying oceans. What drives this constant remodelling? Ultimately, the motive force is the convective circulation of the mantle. New lithosphere is formed at mid-oceanic ridges, where hot magma from the mantle wells up between diverging plates. The new surface material spreads outward from the ridges and eventually plunges back into the mantle at oceanic trenches and island arcs, where two plates collide with each other. Although this model is widely accepted, the origin of the upwelling material and the fate of the subducted plate—in general, the details of the flow in the mantle—have remained unknown, beyond the reach of conventional geophysics and its analytical techniques. Recently seismic tomography has been applied in three-dimensional modelling of the earth's interior[2].

Velocity gradients and triplications

The classical ray theory in seismology is the primary tool for analysis of seismic waves emanating in all directions from a source. Spherically symmetric earth models have been considered in all such cases. The slowness vector, p, which is also known as the ray parameter, can be defined (by considering Snell's law) as

$$p = \frac{r \sin i}{v} \qquad (1)$$

(also, $p = \frac{\mathrm{d}T}{\mathrm{d}\Delta}$, i.e. slope of the travel time curve (2)),

where the seismic ray travelling with velocity v makes an angle i with radius r. At the deepest point of penetration (turning point in the medium) of the rays, angle i is 90°, so that

$$p = \frac{r}{v}. \qquad (3)$$

The above analysis is applicable in regions where velocity increases continuously with depth and any decrease in velocity is so little that $\mathrm{d}v/\mathrm{d}r < v/r$ everywhere in the layer.

However, in the real earth, the problem is not so straightforward. The outer part is quite complex in nature and heterogeneities do persist. Lateral and vertical inhomogeneities have been found to occur even deeper in the upper mantle, and two transition zones or positive high-velocity gradients have been identified near the depths of 400 km and 650 km. Seismic waves behave in a different manner within these zones.

Figure 1,*a* shows the effect of high-velocity gradients on seismic rays. As the ray enters this anomalous zone, it is strongly refracted and reaches the surface by a shorter path. Normally, when the angle of incidence decreases, epicentral distance increases. But in this case, for a limited range of p values, the rays are bounced back to the surface and appear at smaller epicentral distances. Because of the focusing effect, the amplitude of arrivals is larger when such seismic rays are recorded by seismometers at the surface. Figure 1,*b* shows the resulting triplicated travel-time curve (triplication). Several studies on upper-mantle structure have confirmed the presence of these transition zones; Figure 2 shows one example,' the triplicated travel-time branch for the Himalayan region (Figure 2,*a*) and the resulting velocity model (Figure 2,*b*). The 400-km discontinuity has been

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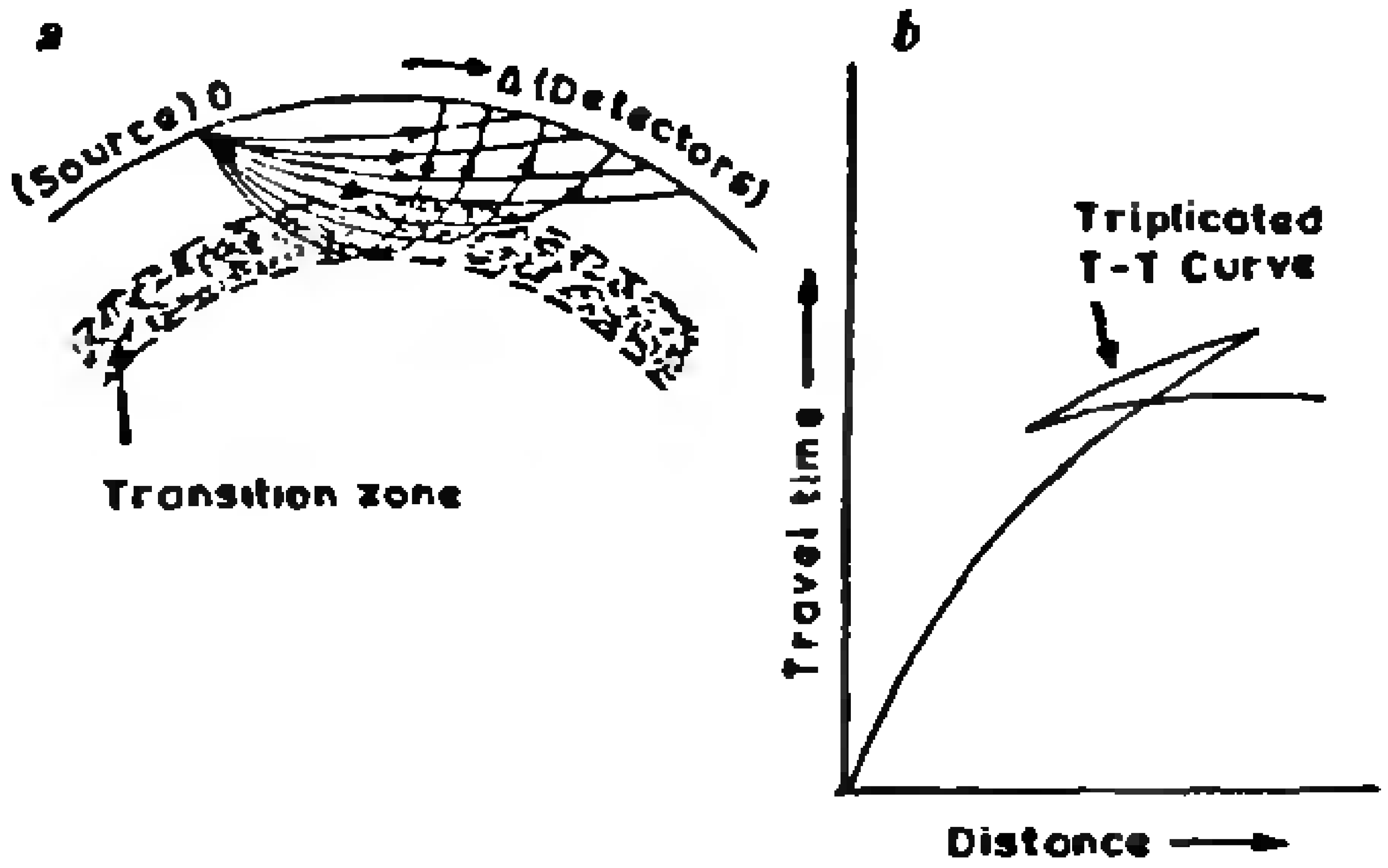

Figure 1. a, Effect of high-velocity gradients or transition zones on seismic waves, and b, the corresponding triplicated branch of the travel-time curve.

found very clearly from the observations. However, the 650-km discontinuity was replaced by a very broad velocity gradient and has not been observed sharply in this region. Figure 2.c shows the corresponding ray-geometry diagram for the velocity model.

Upper-mantle studies

Study of upper-mantle structure with regard to the distribution of P-wave (compressional wave) velocities and lateral and vertical inhomogeneities has been a subject of intensive research. Our understanding of the tectonic processes and forces responsible for phenomena such as plate tectonics and earthquakes depends very much on what we know of the structure of the lithosphere–asthenosphere and how that structure varies from region to region. Because of the non-uniqueness in inversion of seismic data and the difficulties in observing and identifying travel-time branches, interpretation of the results is still very difficult. Hales[3] and McMechan and Sinclair[4] reviewed and compared a large number of upper-mantle models postulated from seismic observations. Although these models differ in detail, most of them point to the existence of discontinuities or larger positive velocity gradients (transition zones) near the 400-km and 650-km depth ranges.

The Indian region

The Indian subcontinent is of particualr interest to geoscientists because of the manner in which the Indian Plate has moved northward and collided with the Eurasian plate. The Himalayan mountains to the north, the mid-oceanic ridges to the south, and the earthquake belts surrounding the Indian plate all show that the lithosphere–asthenosphere structure in the region must have some significant lateral and vertical variations. Analysis of about 200 earthquakes that occurred in the Hindukush and Himalayan regions has revealed a few enigmatic problems, viz. an anomalous zone below the Aravali range at a greater depth in the asthenosphere and the absence of 650-km discontinuity towards the Himalayan side. The nature of P-wave seismic velocities also varies in both directions. The transformation of the sharper 650-km discontinuity in the Himalayan region into a broad high-velocity gradient zone suggests the absence of phase transitions occurring at that depth. This may be due to the northeastward movement of the Indian Plate during the Miocene period when Himalayan orogeny was at its peak.

A number of studies on upper-mantle seismic structure of Indian regions have been carried out. Lukk and Nersesov[5], Tandon[6] and Kaila *et al.*[7] gave upper-mantle velocity models for the Hindukush region. Critical analysis of these P-wave velocity models reveals that they differ with each other in detail. These differences include uncertainties in observations and methods of analysis of the data. Most models are derived on the basis of statistical analysis. Other velocity models were given by Bhattacharya[8] for the Central Peninsula and Western Ghats of the Indian

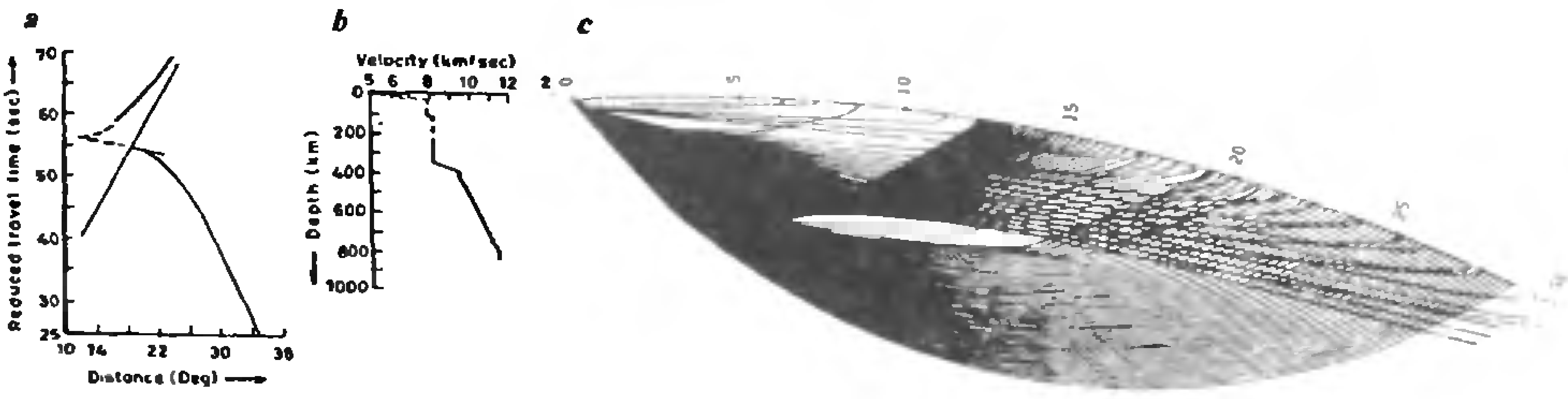

Figure 2. a, Travel-time curve for the Himalayan region, b, the corresponding velocity model and c, the ray-geometry diagram for the velocity model.

subcontinent, and by Kaila *et al.*[9] for the Himalayan region.

With the seismic arrays and sophisticated processing techniques available, it is now possible to measure travel-time gradients ($dT/d\Delta$) or slowness and apparent azimuths directly and automatically for incoming seismic waves crossing an array. The small differences in slowness and apparent azimuths for overlapping phases, especially where the branches of the travel-time curve are triplicated, can in many cases be resolved successfully. Such measurements provide much more detailed and refined upper-mantle models of the earth and may remove some of the ambiguities in interpretation of the data. Ram and Mereu[10] and Ram *et al.*[11] presented such results from seismic array data for the Indian subcontinent and North America. An overview was also presented by Ram and Singh[12] for Indian upper-mantle regions.

Seismic tomography

Computed tomography (CT) is a new method of medical imaging that has revolutionized the field of medical diagnostics. Indirectly, it has led to new developments in its predecessor techniques of radiological imaging and classical tomography. The fundamental principle behind tomography is quite old. Mathematically, the problem is that of estimating an image (object) given its projections (shadows) observed from different directions. In continuous space the projections are simply rays or strip integrals of the image measured for different ray positions and angles[13–15].

During the past few years seismic tomography has promised to enhance our knowledge of the earth's internal structure, including the pattern of flow in the mantle[12]. Like its medical analogue, computer-aided tomography or CAT scanning, seismic tomography combines information from a large number of criss-crossing waves to construct three-dimensional images of the medium seismic rays have traversed. Figure 3 illustrates the basic principle. Seismic waves that cross the inhomogeneous medium from different directions are recorded by an array of seismometers or group of seismic detectors. The slowness or velocity anomaly can then be computed using a standard earth model (see, for example, Jeffreys[16]). Seismic waves that do not pass through the anomalous region show normal travel time for surface distances. The slow and fast regions of the traversed path can be shown by different colours to indicate the zone distinctly.

Body waves as well as long-period surface waves have been used in seismic tomography. Data for this kind of analysis are obtained from digital recording network [Seismic Research Observatory (SRO), World Wide Seismological Stations Network (WWSSN)]

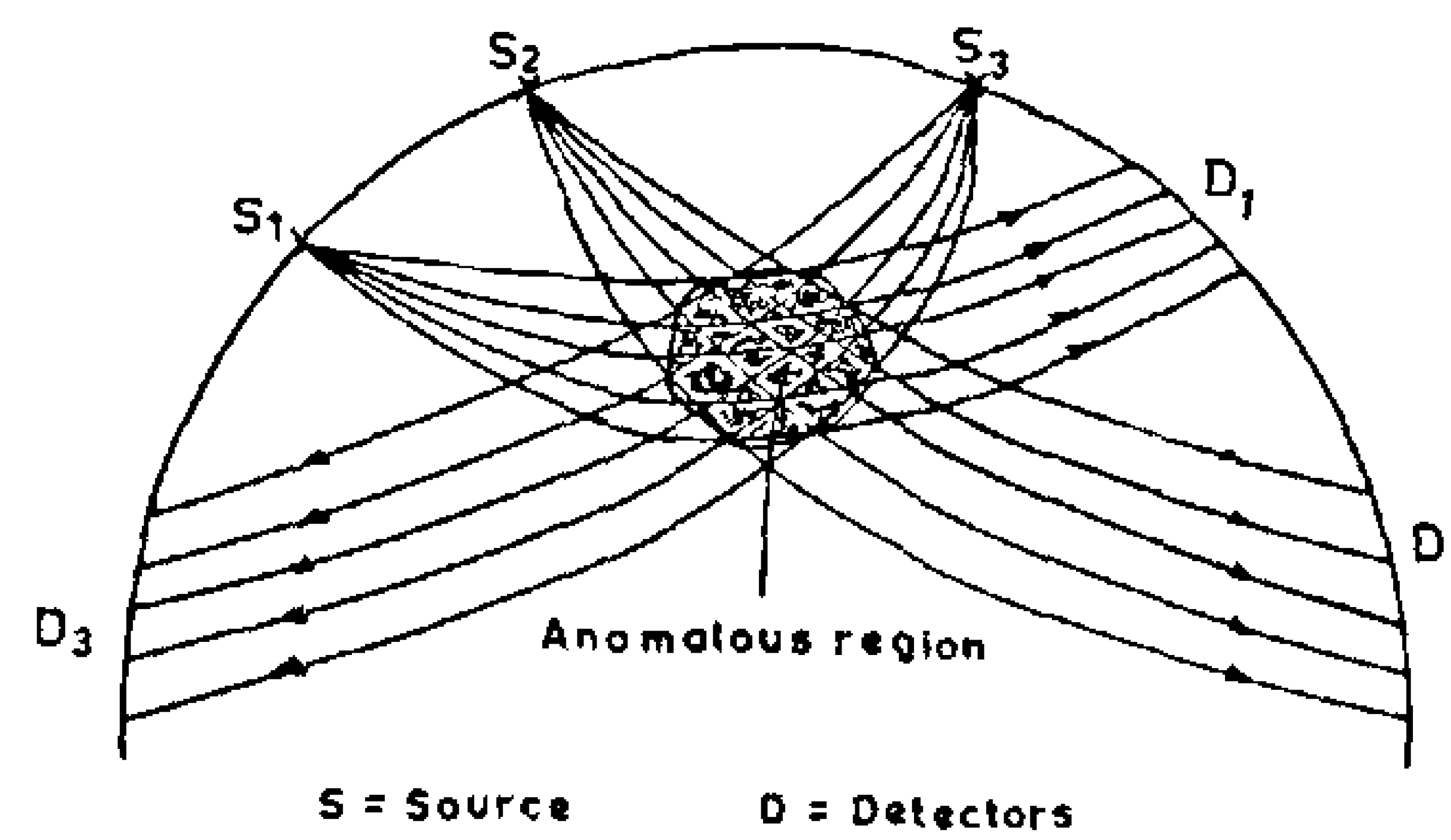

Figure 3. The principle of seismic tomography: the inhomogeneous block of material is criss-crossed by several rays, and an array or group of seismometers detect the anomalous slowness vectors.

stations. However, seismic array data and International Seismological Centre (ISC) arrival time data are equally useful in tomographic research. A set of simultaneous equations for each unit region of the upper mantle can be formulated between a series of terms with associated velocity parameters and known travel time of all the rays being considered. The anomaly vectors from different directions can be tied down to draw a three-dimensional picture of the region, in which anomalous features can be represented by colours.

Discussion

Upper-mantle structure has been a subject of prime importance for decades, especially in the context of the plate-tectonics hypothesis, continental drift, ocean-floor spreading, low-velocity layers, transition zones, and convection currents. Several refined models are now available for the entire tectonic globe that reveal two-dimensional features of the upper mantle. Efforts are now directed at deriving a three-dimensional model of the earth's structure. A statistical technique based on Chernov random medium approach provides estimates of RMS velocity perturbations in the lithosphere in an array siting area, the extent of inhomogeneities (or inhomogeneous medium), and the correlation distance. The last parameter is a measure of the wavelength of the structural anomalies. Aki *et al.*[17,18] and Husebye *et al.*[19] inverted the travel-time residuals from Large Aperture Seismic Array (LASA) and Norwegian Seismic Array (NORSAR) data and obtained a three-dimensional image of seismic-velocity anomalies in the upper mantle. Berteussen *et al.*[20] also made a similar study from Gauribidanur seismic array (GBA) data. Gaur *et al.*[21] used such a technique to study the extent of the Deccan Traps. Ram and Yadav[22] indicated that the source of the traps may be in the vicinity of 25 N, 75 E.

A large number of P-wave velocity models for upper-mantle structure in different regions of the earth agree in general on the presence of the two major transition zones associated with the 400-km and 650-km discontinuities. A few have shown the occurrence of high-velocity gradients below 700-km depth[23]. The non-uniqueness in the velocity models can be attributed to signal complexity and variability[24], and identification of later arrivals and consequent positioning of the travel-time branches.

Lukk and Nersesov[5] reported comparatively higher P-wave velocity for the Hindukush region. They also found a low-velocity layer at 110–150-km depth. Tandon[6] applied Gutenberg's[25] formula to derive velocity distribution of P-waves. He could not clarify whether the lack of observations between 12° and 15° epicentral distance was due to the absence of observing stations at these distances or due to the existence of a shadow zone. Gutenberg's method is not suitable when there is a sudden decrease in the velocity. Moreover, this method is a graphical one and the apparent velocity near the point of inflexion depends very much on the slope of the curve drawn around the point of inflexion (which is difficult to locate). Derivation of the low-velocity channel by Tandon[6] from S-wave data was also based on this graphical technique. This may not be fully justified as Tandon did not find any evidence for a similar layer while analysing the P-wave data. Kaila *et al.*[7] used the analytical technique for determination of P- and S-wave velocities in the upper mantle. In an earlier report[9], the uncertainties in the depths of the discontinuities are large, which, in turn, are a reflection on the accuracy of the method of interpretation. Two models have been derived by Bhattacharya[8] using dispersion of surface waves. He has found evidence for anisotropy for S-waves in the depth range 60–160 km in the central part of the Indian peninsula. However, he does not mention such evidence for P-waves.

Ram and Mereu[10] carried out an upper-mantle study using GBA data for the Indian subcontinent as well as oceanic regions. Figure 4 illustrates an example from

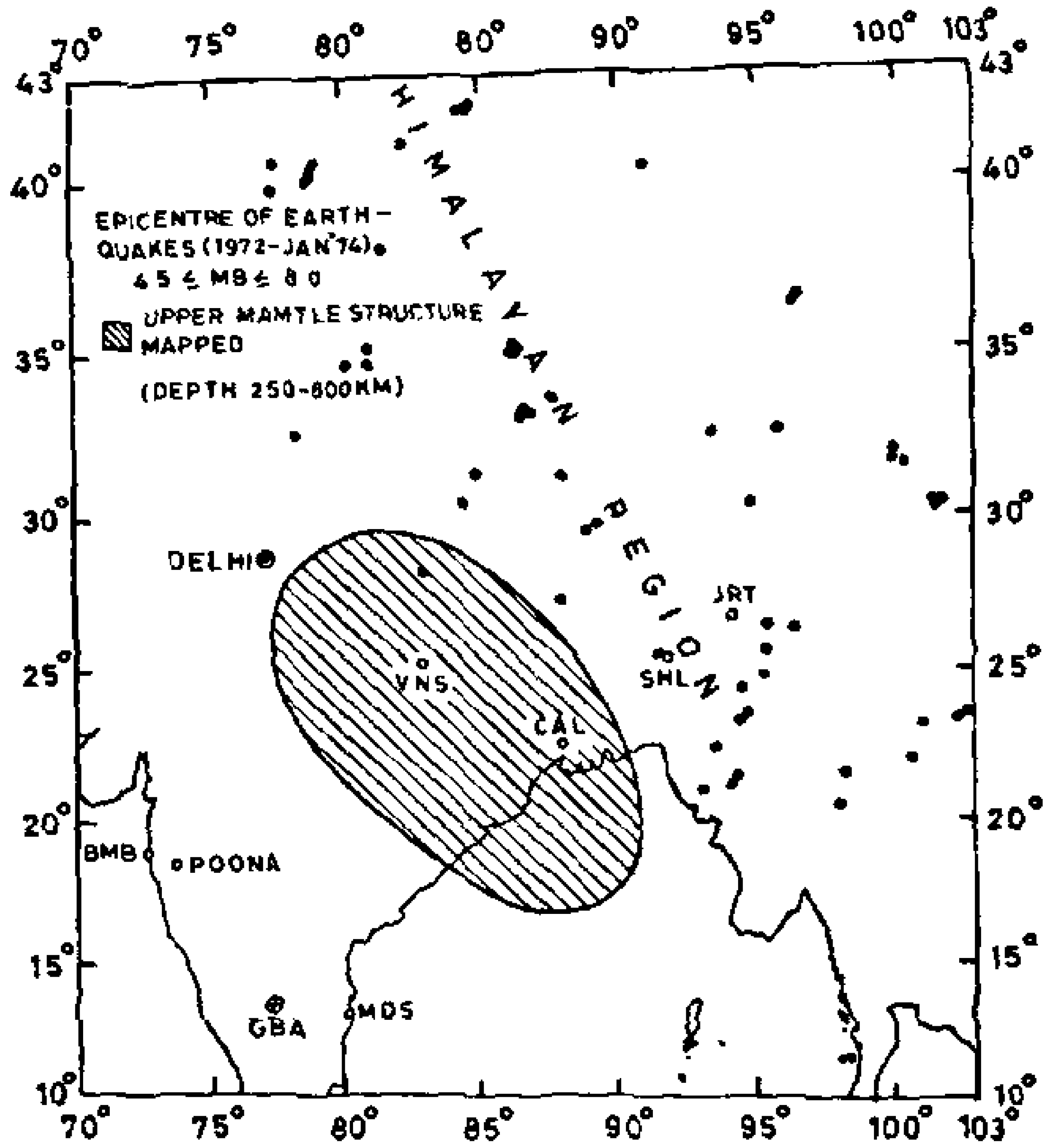

Figure 4. Postulated upper-mantle structure (hatched region) related to the slowness anomalies shown in Table 1.

Table 1. Slowness anomalies for Himalayan earthquakes

Identification number	Slowness anomalies	Identification number	Slowness anomalies	Identification number	Slowness anomalies
47 GBA	−0.01	201 GBA	0.65	312 GBA	−0.09
52 GBA	−0.94	204 GBA	0.63	6 GBA	−0.16
63 GBA	−0.04	205 GBA	0.74	7 GBA	−0.40
117 GBA	−0.99	221 GBA	−0.25	8 GBA	−0.03
119 GBA	−0.25	224 GBA	0.20	9 GBA	−0.48
120 GBA	−0.35	226 GBA	−0.13	18 GBA	−0.38
126 GBA	−0.13	234 GBA	0.11	25 GBA	0.36
133 GBA	−0.23	235 GBA	−0.14	28 GBA	−0.49
138 GBA	0.29	237 GBA	0.67	29 GBA	0.15
144 GBA	−0.06	244 GBA	0.32	34 GBA	−0.21
145 GBA	−0.09	245 GBA	−1.26	65 GBA	−0.05
146 GBA	−0.46	248 GBA	0.54	68 GBA	−0.69
160 GBA	−0.31	249 GBA	−0.17	69 GBA	−0.51
162 GBA	−0.34	251 GBA	−0.49	88 GBA	1.05
174 GBA	0.05	265 GBA	0.68	96 GBA	−0.57
178 GBA	−0.01	267 GBA	0.06	101 GBA	−0.02
188 GBA	1.59	268 GBA	−0.09	102 GBA	0.04
189 GBA	0.73	270 GBA	−0.09	109 GBA	0.29
190 GBA	1.36	276 GBA	−0.41	185 GBA	1.53
191 GBA	1.30	281 GBA	0.82	208 GBA	−0.41
195 GBA	−0.25	289 GBA	−0.38	209 GBA	−0.51
197 GBA	−0.13	295 GBA	−0.73	210 GBA	−0.49
199 GBA	0.14	309 GBA	0.55	273 GBA	−0.12
				316 GBA	0.50

data on Himalayan earthquakes. The hatched area has been mapped between depths 250 and 800 km using the slowness (or velocity) anomalies shown in Table 1. Ojo and Mereu[26] found regional differences in upper mantle heterogeneity from coherency measurements on array data. They also confirmed that vertical variation exists in the heterogeneity of the upper-mantle structure between GBA and the Himalaya to the northeast. We are now processing these anomalies for a three-dimensional model using modern techniques of seismic tomography. However, Menke[27] recently pointed out limitations of the tomographic approach.

Proposals

Some of the most important problems related to the Indian lithosphere–asthenosphere structure can be addressed by installing additional seismological stations at intervals of 2–3°. Regions like the southern tip of India, the lesser Himalaya and the east coast must be covered with suitable instrumentation. Studies on crust–upper-mantle structure of Rapti basin, Ganga basin, Bengal basin and regions off the eastern coast (oceanic) are important because of the presence of possible hydrocarbon-bearing structures there. Fine structural variations in the Indian lithosphere may further be obtained by accurate positioning of cusps of travel-time branches associated with different transition zones of geodynamic processes and systems. Modelling may be achieved by considering such phenomena as scattering and attenuation (Q profiles) of seismic waves for the Indian oceanic and continental regions. Lateral and vertical inhomogeneities and anisotropy problems may also be resolved subtly.

As part of an innovative and viable research programme to study the Indian lithosphere–asthenosphere region and the characteristics of the plate, a tripartite seismological array network station at Banaras Hindu University can record, monitor and analyse of seismic events occurring in the Pamir–Hindukush–Himalayan-belt region for a continuous period of 3–5 years. This should provide better understanding of the geodynamic processes in this geologically complex region of the world.

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