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Seismotectonics of the Western Himalayas: Application to Earthquake Hazard and Collisional Tectonics

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Table of Contents

Executive Summary:

The principal objective of this project is to better understand the crust-uppermantle structure and the state of stress and seismic hazard within the Pakistan Himalayas and surrounding regions. During the first year (August 30, 1990, to August 31, 1991) we studied instrumentally located earthquakes reported by the International Seismological Center and negotiated with the Water and Power Development Authority of Pakistan (WAPDA) for a temporary deployment of a 11 station seismic array in the Pakistan Himalayas. During the second year (September 1, 1991, to August 31, 1992) we studied earthquakes in the Pamirs and Karakorum and prepared for the deployment of the temporary seismic array in the Pakistan Himalayas. The early part of the third year (September 1, 1992, to December 1992) we deployed and operated a 11 station temporary seismic array in the Pakistan Himalayas. During this period we trained Pakistani scientists to operate digital seismic recording systems, and left computer programs and a complete set of data with WAPDA. The remaining period of this grant we analyzed the data collected in Pakistan and sent the archived data to the Data Management Center, Incorporated Research Institutions for Seismology (IRIS). We have obtained funding from NSF to support two Pakistani collaborators to visit U.S. in 1996 and discuss a geotravese which will extend from northern Pakistan to western China.

Through our research we found that moderate-sized subcrustal events that have occurred in the Nepal Himalayas could occur in the western Himalayas. A detailed three-dimensional analysis of the velocity structure beneath the western Himalayas reveals a buried foreland basin. We speculate that this basin may trap gas and oil. Thus, the seismic results may eventually lead to new discoveries in oil and gas in the Pakistan Himalayas. The data from the temporary seismic deployment indicate there is no appreciable large-scale azimuthal anisotropy beneath this part of the Himalayas. Therefore, if there is any significant strain in the uppermantle beneath this area, it must be vertically oriented.

Research Objectives:

The overall aim of the project is to investigate in some detail that part of the Himalayan collisional belt located in northern Pakistan which forms the Hazara Arc and the Hazara-Kashmir syntaxis. The Himalayas/Tibet plateau collision zone is the type example of active continent-continent collision on the Earth. It encompasses the largest area of elevated topography and correspondingly, the largest area of overthickened continental crust on the planet, and it is a natural laboratory within which to study such basic issues of continental dynamics as the response of continental lithosphere to shortening, collisional magmatism, delamination, denudation, and the interplay between erosion and tectonics. At a basic level, each of these issues is tied to the fundamental question: How is the crust within the Himalayas/Tibet plateau collision zone thickened? The goal of this project is to address this fundamental question through direct imaging of the crust and mantle beneath the Pakistan Himalayas.

This project was the culmination of more than a decade of effort by U.S. and Pakistani investigators to initiate a field seismic program within the Himalayas/Tibet Plateau collision zone. Field deployment become a practical possibility in 1990 when the Water and Power Development Authority of Pakistan (WAPDA) was interested in collaborating with New Mexico State University on a Pakistan project. The field work carried out in Pakistan in 1992 was the first deployment with modern seismic equipment.

Superimposed phases of thrusting involving basement rocks and imbrication of metamorphic zones have been recognized in the Pakistan Himalayas. An upper crustal wedge at 12- to 24-km depth beneath the western limb of the Hazara-Kashmir syntaxis has been imaged by inverting travel time data recorded at fifteen Tarbela seismic stations. It appears that the Indian plate bends steeply beneath this wedge and continues to underthrust beneath the High Himalayas. An important question is whether this crustal wedge represents a "flake" of the Indian basement or a major break through the entire Indian crust. Some of the important tectonic questions to be addressed are: how much of the basement materials are involved in the flaking processes, how is the Indian plate deformed as it underthrusts the Himalayas, and what is the degree of shear heating and melting related to interplate thrust faulting at depth.

The specific subjects to be investigated as part of the proposed project are:

- The geometry of the underthrusting Indian plate beneath the Hazara Arc.
- The state of stress at different crustal levels.
- The importance of strike-slip faulting in regions adjacent to the western Himalayan Syntaxis.
- The nature of deformation within the foreland fold and thrust belt.
- The relation between surface and subsurface deformation.
- The relation of observed seismicity to seismic hazard.

Each of these objectives is crucial to understanding the tectonics of collisional mountain belts and associated seismic hazards. Because most of the large events in the western Himalayas appear to have occurred along a decollement at the top of the Indian plate, the delineation of this boundary is essential to understanding these earthquakes. The presumed dip of this surface is based on a handful of epicenters, gravity data, and seismic reflection profiles from oil and gas exploration in the foreland; the exact geometry in the hinterland remains to be discovered.

Methods and Results

Data used in this project consist of (1) seismograms and phase information collected from the Tarbela seismic network, (2) data collected by the World Wide Seismic Networks and (3) data collected by the 11 station temporary array. Standard seismic analysis methods are used to exact structure and physical parameters in the western Himalayas. Following is a brief account of major findings:

The Tarbela telemetered network consists of 15 short-period, high gain (magnification of one million at 5 Hz), vertical component seismic stations and is located in the Hazara Arc (Figure 1). Earthquake arrival times from approximately 8000 local events with local magnitudes varying from -3.5 to 4.9 were recorded at this array from August 1973 to August 1976. Out of the 8000 recorded earthquakes, 1495 are located within the area encompassed by the Tarbela Seismic Network. The hypocenters range in depth from near surface to 70 kilometers. In order to insure accuracy and stability in the three-dimensional velocity inversion, we selected 420 events based on the accuracy of location and the standard deviation of arrival time residuals. P and S wave travel times from these 420 events to each station are used in the inversion routine.

In solving for the three-dimensional velocity structure we use the "block" inversion scheme modified by us. This method determines heterogeneous structures by perturbing a simple plane layered model that represents the average one-dimensional velocity structure of the region under study. Using a least squares method, the P and S velocities are perturbed simultaneously with hypocenter locations to minimize the travel time residuals of both P and S arrivals. The solution is obtained iteratively, and the variance improvement is checked after each iteration. Iterations are brought to an end when there is no longer a significant reduction in the residual variance.

A three-dimensional P and S wave velocity structure and hypocenters of 420 events beneath the western Himalayas are obtained simultaneously by inverting travel time data observed at fifteen Tarbela seismic stations (Figure 1). The results indicate a low-velocity zone immediately to the west of the western Himalayan Syntaxis (near Muzaffarabad, Pakistan) (Figures 2 and 3). This low velocity zone is interpreted as a buried foreland basin. We speculate that this basin may trap gas and oil. Thus, the seismic results may eventually lead to new discoveries in oil and gas in the Pakistan Himalayas.

Velocity structures also indicate that the top surface of the underthrusting Indian plate dips gently, about 6° until it reaches the southern Higher Himalayas. A prominent NW trending seismic zone, the Indo-Kohistan Seismic Zone (IKSZ) which extends northwesterly along the main Himalayan trend is interpreted as a major fault that separates the Lesser Himalayas from the Higher Himalayas. Many large earthquakes, such as the December 28, 1974, magnitude 6.0, Patan earthquake have occurred along this zone. We believe this seismic zone poses the most danger to the nearby Tarbela dam.

We studied instrumental earthquakes reported by the International Seismological Center. Focal mechanisms of moderate-sized earthquakes were determined. These mechanisms are mostly thrust mechanisms and show predominantly NW-SE oriented fault planes, parallel to the structure trends of the Himalayas. We also studied the 1934 Bihar-Nepal earthquake. Forward modeling of P-wave seismograms indicates that the 1934 event has a focal depth of 22±6 km. The favored mechanism has a shallow thrust plane: strike = 291°, dip = 34° and rake = 64°. The dip is constrained ± 10°, while the rake no better than ±20°. The source time function is 18 seconds long, and the seismic moment was determined to be 4.1 x 10^{27} dyne-cm. The moment is significantly smaller than would be indicated by the 8.3 magnitude, probably the result of the limited instrument frequency band. The epicenter location and the depth suggest that this event occurred in the base of the greater Himalayas rather than the Gangetic foredeep. The occurrence of this event implies that similar sized events will occur along the base of the western Himalayas.

The spatial distribution of earthquake hypocenters and earthquake fault plane solutions is used to investigate the three-dimensional configuration of lithosphere that is subducted beneath the Pamirs and Karakorum and how crustal deformation is accommodated in the Pamirs-Karakorum collision zone. Fault plane solutions of 48 earthquakes, including 18 new solutions, are correlated with tectonic features of the region. Convergence between the Pamirs and the southern boundary of the Eurasian Plate is occurring along the Northern Pamir Thrust and several major faults, all which are marked by a narrow zone of seismicity. Most of the earthquakes which occurred in these fault zones are shallow crustal events. Fault plane solutions determined from the inversion of teleseismic long-period body waves show predominantly thrust faulting along the Pamir Front. Along the western and eastern edges of the Pamirs the style of deformation is characterized by oblique thrusting with a component of strike-slip motion. Thrust-type events beneath the Tadjik Depression indicate that both the sedimentary rocks and the basement are involved in the shortening. Right-lateral strike-slip motion is observed on the eastern edge of the Pamirs, where it borders the Tarim Basin, as well as in the Talas-Fergana-Kunlun fault zone. A south-dipping zone of earthquake hypocenters beneath the Pamirs and Karakorum indicate that the lithosphere of Tarim and Tajik Basins has been subducted along the northern Pamir to a depth of over 200 km. This interpretation is consistent with published geological and geophysical data, which have documented thin-skinned folding and thrusting in the Peter the First Range. Fault plane solutions of some intermediate-depth events beneath the Pamirs show strike-slip faulting with approximately N-S horizontally oriented P-axes indicating that horizontal compression at intermediate-depth is the dominant mode of deformation. A 90 km deep event beneath the Karakorum is interpreted as occurring in the subducted Asian lithosphere; the P-axis of this event oriented parallel to the descending plate suggests down-dip compression within the Asian lithosphere. This is perhaps due to resistance encountered by the northward advancing Indian lithosphere.

Elucidating the deep structure of the present-day active collisional plate boundary of the Himalayas is the key element in understanding the evolution of collisional mountain belts. In order to achieve this goal we have deployed a PASSCAL portable broadband array in the western Himalayas. From September 27, to December 10, 1992 (74 days), 9 broadband Streckeisen STS-2 sensors, 11 Mark Products L-22D, 2.0 Hz short-period sensors, and Reftek digital recording systems equipped with 330 Mb hard disks were deployed across the Himalayan Front in Pakistan. The seismic array, covering a region of about 160 by 100 kilometers, spanned the Lesser Himalayas and the Higher Himalayas. Scientists from Tarbela Dam, Water and Power Authority of Pakistan assisted us in deploying and collecting data. We also gave training lectures to junior seismologists at Tarbela Dam on various seismic methods. The data set collected from this array is sufficiently large to determine the crust and mantle velocity structures across the Himalayan Front in Pakistan and to study the regional wave propagation in Pakistan and surrounding regions.

About 200 local events and 700 Hindukush intermediate-depth events were recorded by our array. Seismic energy radiated from 100 to 300 kilometer deep earthquakes will enable a detailed study of the Moho geometry. Seismograms from many local and regional events (earthquakes and quarry blasts) are available for the investigation of regional-phase spectra (Pn, Pg, Lg, and Sn), and amplitude ratios. Characterization of these regional and local waveforms will form a basis for seismic-event identification in the western Himalayan region. Radial receiver functions are used to investigate the shear-wave velocity structure of the crust. Intermediate-period surface waves recorded by the Pakistan broadband seismic array will be used to determine phase velocities in the western Himalayas. The phase velocity data will be inverted to determine the crustal velocity structures beneath the Himalayan Front. A better knowledge of the upper mantle structures will help in understanding the dynamics that control the seismic activity and tectonic deformation presently taking place in the western Himalayas.

Shear-wave splitting observations constitute another important way in which to characterize mantle deformation beneath the Himalayan Front. Teleseismic S, SKS and SKKS data are analyzed for shear-wave splitting parameters. No receiver-side splitting was observed in any of the S wave data. The lack of shear-wave splitting beneath the Pakistan Himalayas indicate that there is no appreciable large-scale azimuthal anisotropy beneath this part of the Himalayas. Thus, if there is any significant strain in the upper mantle beneath this area, it must either be vertically oriented, or if horizontal, vertically vary in such a way that the integrated effect on the S wave splitting is null.

Forward modeling of P to S converted phases from intermediate depth Hindukush earthquakes indicate crustal thickness of about 46 km beneath the Tarbela Dam. Receiver functions generated from seismograms of a 400 km deep event near Japan indicate conversion at the top of the underthrusting Indian plate and at the Moho. However, the converted phase at the Moho is not observed at some stations indicating a complex Moho and other dipping boundaries in the Indian lithosphere. We are aware of the limitations of the receiver function technique, especially in regions of large lateral velocity changes. Thus, we think the best techniques for resolving the deeper structures are forward modeling of P and S waveforms from deep Hindukush events and stacking many radial components generated by the deep Hindukush events.

Effective seismic event identification of explosions and earthquakes remain a major goal in the nonproliferation issue. For the Western Himalayas and surrounding regions, the problem has been a lack of recorded local and regional events. For example, how the topography and rough Moho discontinuity would effect regional wave propagation is not well known. The data collected in Pakistan are used to test some of the existing models that generate synthetic regional waveforms. A few earthquakes recorded in eastern Iran will provide limited data to examine the Pn, Pg, Lg, and Sn wave propagation. Regional data will also be used to produce amplitude ratios.

Impact, Relevance and Technology Transfer:

Findings from the detailed seismological studies carried out during the course of this project indicate that the Indo-Kohistan Seismic Zone (IKSZ) which extends northwesterly along the main Himalayan trend is a major fault that separates the Lesser Himalayas from the Higher Himalayas. Many large earthquakes, such as the December 28, 1974, magnitude 6.0, Patan earthquake have occurred along this zone. We believe this seismic zone poses the most danger to the nearby Tarbela dam.

A detailed three-dimensional analysis of the velocity structure beneath the western Himalayas reveals a buried foreland basin. We speculate that this basin may trap gas and oil. The results of the travel-time tomography study were used by the Pakistan scientists as a reference for seismic hazard assessment in the northwestern Himalayas.

We gave training lectures to junior seismologists at Tarbela Dam on various seismic methods. Computer codes were left with the Pakistani seismologists and these codes will enhance their productivity. The data set collected from the 11 station temporary array is sufficiently large to determine the crust and mantle velocity structures across the Himalayan Front in Pakistan and to study the regional wave propagation in Pakistan and surrounding regions. Regional wave propagation studies using data collected by this project are being carried out in U.S. and Pakistan and are relevant to the nonproliferation issues.

Project Activity /Output:

Training lectures (Fall, 1992) were conducted in Pakistan during the deployment of the seismic array.

Attended 1991, 1992, 1993, and 1994 Annual Fall Meeting, American Geophysical Union, San Francisco and presented various results at this meeting.

Project Productivity:

Within the scope of the proposed project we have accomplished more than originally envisioned.

Three refereed articles were published in prestigious journals:

Ni, J., A. Ibenbrahim and S. W. Roecker, 1991, Three-Dimensional Velocity Structure and Hypocenters of Earthquakes Beneath the Hazara Arc, Pakistan: Geometry of the Underthrusting Indian Plate, Journal of Geophysical Research, Vol. 96, No. B12, 19,865-19,877.

Sandvol, E., J.F. Ni, T.M. Hearn, and S Roecker, 1994, Seismic azimuthal anisotropy beneath the Pakistan Himalayas, Geophysical Research Letters, Vol. 21, No. 15, 1635-1638.

Fan, Guangwei, J. Ni, and T.C. Wallace, Active tectonics of the Pamir and Kakakorum, Journal of Geophysical Research, Vol. 99, No. B4, 7,131-7,160.

Future Work:

We plan to host one or two Pakistani visitors for three weeks in the early summer of 1996. We will discuss the possibility of a geotraverse extending from northern Pakistan to western China.

Data collected during the 1992 field season are still being analyzed. Regional wave propagation studies are ongoing at New Mexico State University under funding from Air Force Office of Scientific Research and we hope this new knowledge will add to our efforts in solving the problems associated with nonproliferation.

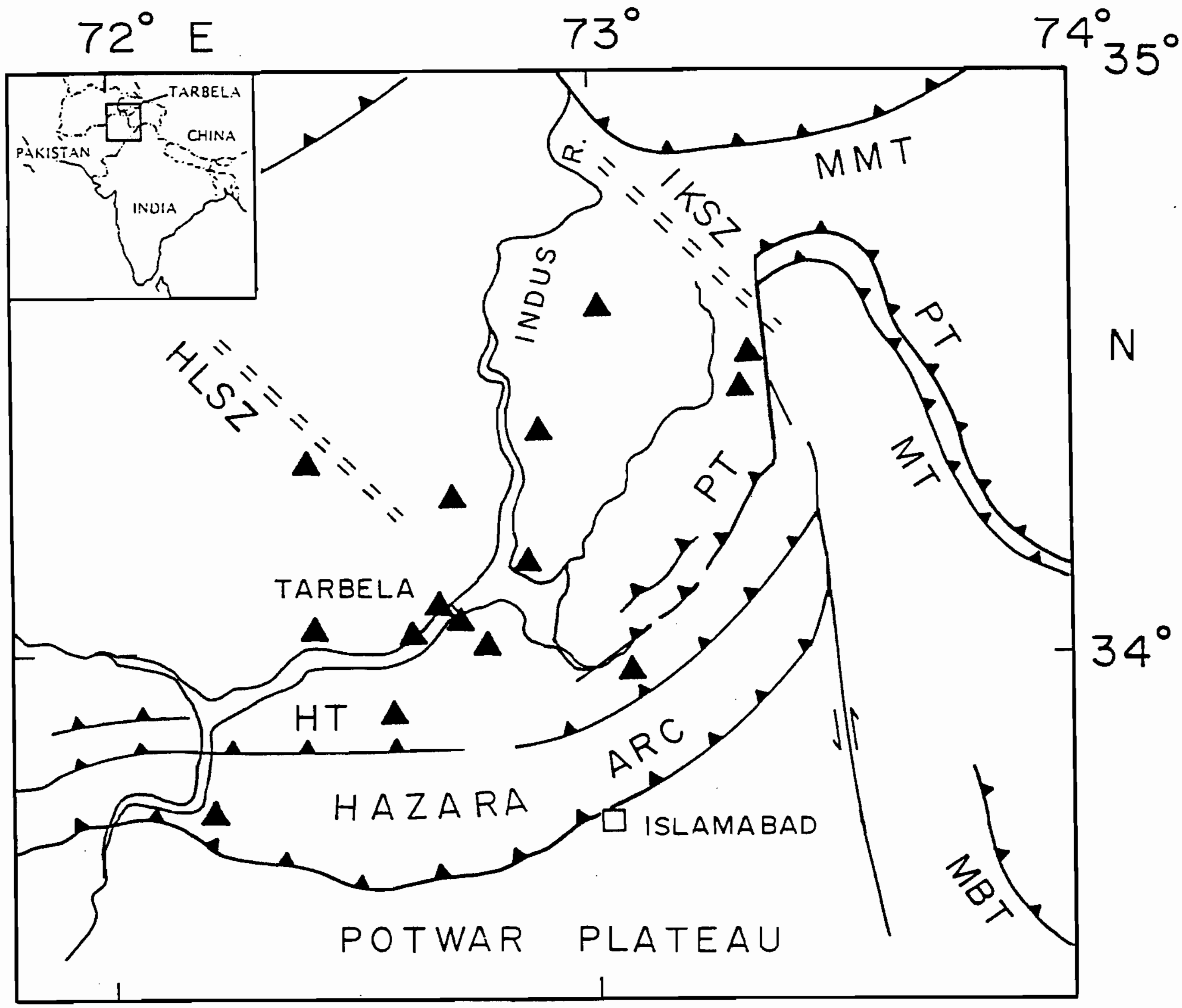

Figure 1. Locations of seismic stations whose records were used in the determination of the P and S wave velocity structure.

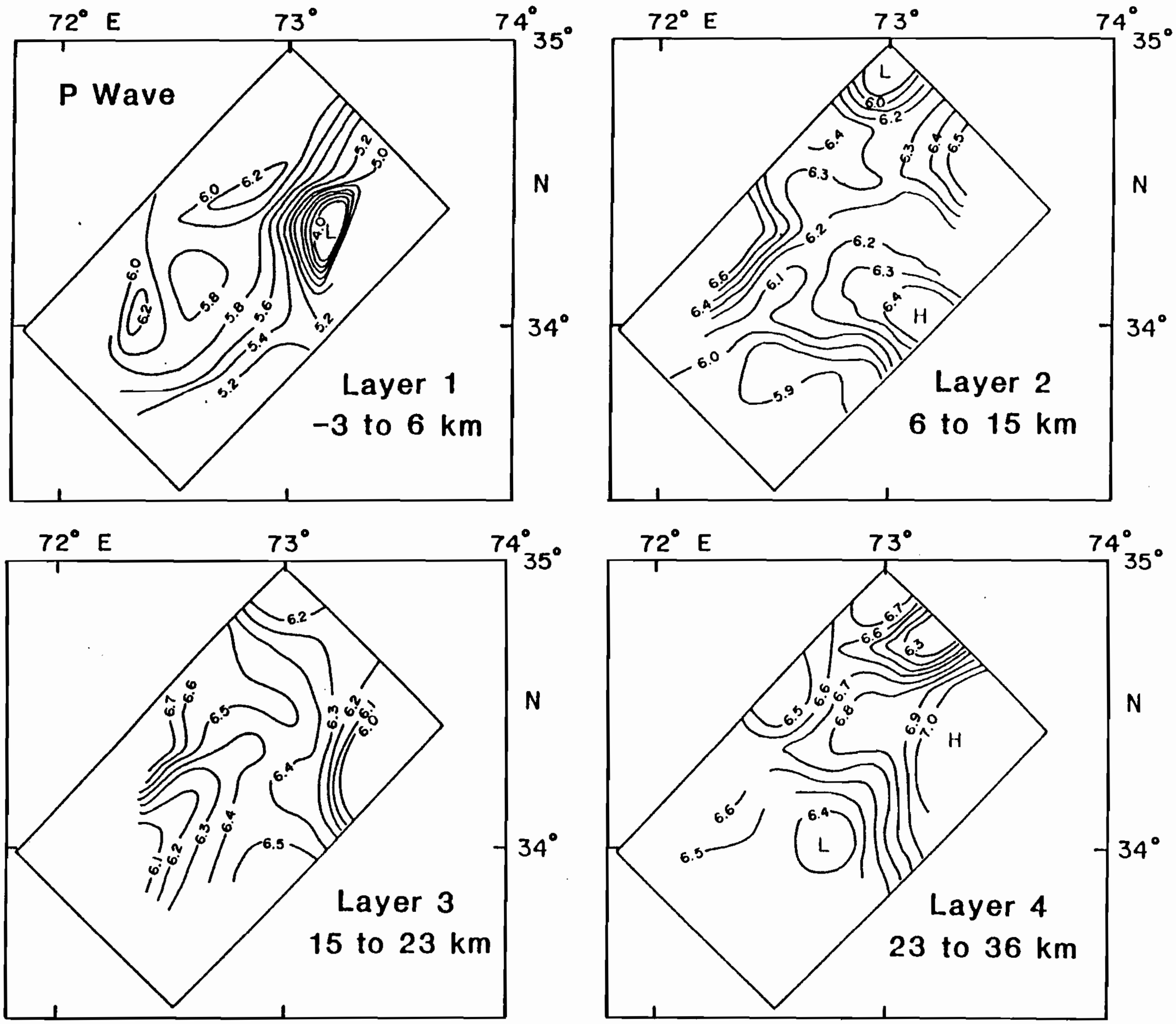

Figure 2. Contours of the P wave velocity structures.

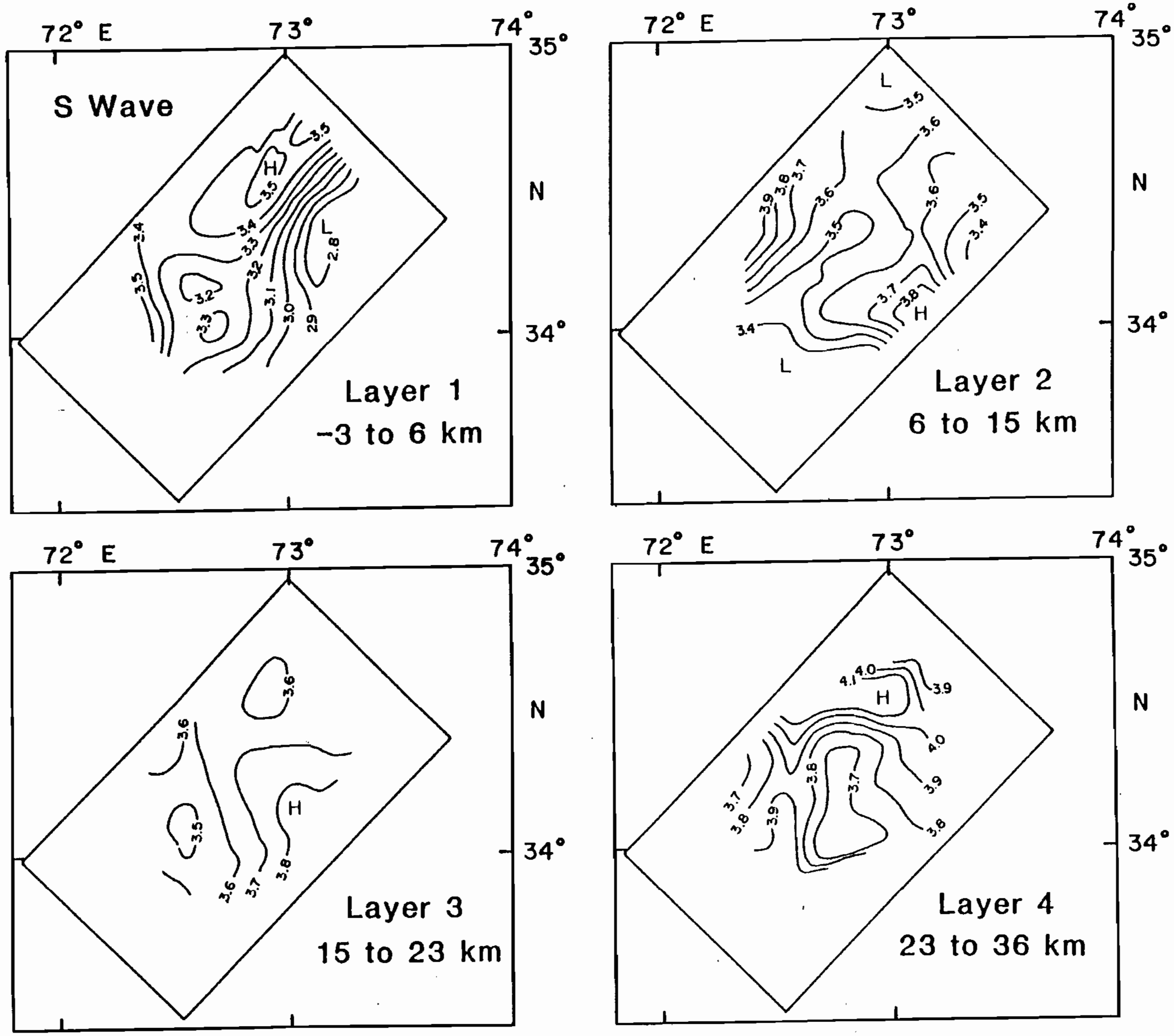

Figure 3. Contours of the S wave velocity structures.