Identification of potential areas for the occurrence of strong earthquakes in Himalayan arc region

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Abstract. Morphostructural zoning (MSZ) scheme of the Himalayan arc region as obtained from a joint study of topographic, geological and tectonic maps as well as satellite imagery is analysed. Three types of morphostructures have been determined: territorial units (blocks of different ranks), linear zones limiting these blocks (lineaments) and intersections of the lineaments (knots). Comparison of MSZ scheme with the known seismicity indicates epicenters of strong earthquakes ($M \geqslant 6\cdot5$) clustered around some of these knots. Pattern recognition method is used to determine seismically potential areas for the occurrence of strong earthquakes of magnitude $\geqslant M_0$. We have carried out two such studies for the Himalayan arc region, one for $M_0 = 6\cdot5$ and the other for $M_0 = 7\cdot0$. Out of a total number of 97 knots, 48 knots are found to be seismically potential for the occurrence of earthquake of $M \geqslant 6\cdot5$. The results of the study for $M_0 = 6\cdot5$ were presented in the symposium on "Earthquake Prediction" held in Strasbourg, France, March 1991 (Gorshkov et al 1991). The epicenter of Uttarkashi earthquake of magnitude, $M_b = 6\cdot6$ that occurred in the late hours of 19th October 1991 (UTC) lies in the vicinity of one such knot. The second study carried out subsequently shows that only 36 knots are potential for the occurrence of earthquakes of $M \geqslant 7\cdot0$, which include the knot associated with the Uttarkashi earthquake.

Keywords. Himalaya; morphostructural zoning; lineament; knot; pattern recognition; earthquake potential.

1. Introduction

The Himalayan arc region, the highest mountain chain on the earth stretching for about 2400 km between Kashmir in northwest India and Indo-Burma border in the east, is a well-known region of high seismic potential. In the light of plate tectonics theory, recent morphostructures of the Himalaya have been formed as a result of continent–continent collision between India and Eurasia. Interaction of these plates which started since Upper Cretaceous is still going on at the present time and is causing a high level of seismicity in the area.

Different sectors of the Himalayan region, however, have not experienced and may not experience the same level of seismicity in terms of frequency and magnitude. It is therefore necessary to distinguish the small territories of high seismic potential from those of less seismic potential within the large Himalayan arc region. Different approaches can be used for this purpose. One such approach is to determine zones of high seismic potential based on the analysis of geotectonic and morphostructural information and subjecting the same to an appropriate pattern recognition algorithm.

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In this approach the objects of recognition are the intersection points of two or more lineaments called *knots*. The numerical parameters extracted from the morpho-structural features around these knots describe the object–vector. Appropriate recognition rules are derived using learning material and they are applied to the set of unclassified objects to classify them into the seismically potential or non-potential class. This method was successfully tested in many seismic regions of the world: Pamirs, Tian–Shan, Caucasus, Anatolia, Balkans, Italy, Alps, Pyrenees, California, Andes (Gelfand *et al* 1972; Rantsman 1979; Filimonov *et al* 1989).

The first attempt to apply pattern recognition method for the determination of earthquake prone areas in the Himalayas was made by Varunoday *et al* 1979, on the basis of geological data. In our study we investigate this problem using pattern recognition algorithm on morphostructural data.

Morphostructural knots form the objects for recognition in our study because of the fact that all the known epicenters of strong earthquakes are found located in the near vicinities of such knots. It is further hypothesized that the epicenters of future earthquakes would also be associated with knots. The validity of this hypothesis is discussed by Rantsman (1979) and the statistical testing by Gvishiani and Soloviev (1981).

2. Morphostructural zoning of mountain territories

Morphostructural knots, denoted as the objects of recognition of possible strong earthquake areas, are determined from a scheme of morphostructural zoning (MSZ). MSZ is based on the idea about block structure of the earth's crust. MSZ means the division of a territory into a system of hierarchically-ordered areas characterized by a definite degree of uniformity of the morphostructure.

Morphostructural analysis is based on the concept that tectonic movements have brought about changes in the earth's surface. This forms a part of earth sciences that deals with the relations between landforms and recent tectonic movements. It is a part of structural geomorphology, the purpose of which is to analyse all relations between geological structures and geomorphology. Determination of earthquake prone areas using recent relief data is based on the concept that the large elements of relief in the mountain territories represent in some way or other the tectonic movements at the depth comparable with those of shallow earthquakes.

Three types of morphostructures are identified in MSZ: territorial units (blocks); linear zones separating blocks (morphostructural lineaments); and the intersections of various lineaments (morphostructural knots). Blocks, lineaments and knots – in that order, are characterized by an increasing tectonic activity.

MSZ is hierarchically ordered and blocks are assigned with ranks. Mountain countries – considered as blocks of first rank – are divided into blocks of second rank called as megablocks. Megablocks are further subdivided into blocks of third rank called blocks. The rank of lineaments is also decided as first, second and third depending on their relation to mountain countries, megablocks and blocks respectively.

Morphostructural lineaments are zones of varying width upto a few tens of kilometers depending on the rank and their position against large relief elements. Longitudinal lineaments are generally parallel to the predominant strike of large elements of relief. They occur along the boundaries of these elements, separating the relatively

elevated areas from those of lower elevation. Longitudinal lineaments are also characterized by contrasting types of relief and include the zones of large faults. Transverse lineaments are oriented across or at an angle to the predominant strike of large elements of relief. Their manifestations on the surface are normally discontinuous.

The knots include areas greater than the width of lineament zones that form the knot. The actual boundaries of the knots must be defined by field geomorphological investigations. In the absence of field investigations the boundary is considered as a circular area of a given radius around the knots. The centers of such circles are the points of intersections of lineaments. Radius of these circles is determined on the basis of the magnitude of the earthquake under consideration.

3. Morphostructural zoning of the Himalaya

The MSZ-scheme of the Himalaya (figure 1) is constructed in accordance with the rules described above. The main inputs used for this study are topographic, geological and tectonic maps as well as satellite imagery.

Four main tectonic zones are usually recognized in the Himalaya (Ganser 1964). They generally correspond to different hypsometric levels within southern and northern flanks of the Himalaya.

According to MSZ principles, the Himalaya is considered as a continuous mountain country with a common type of orogenesis and uniform appearance in relief. From Ganser's (1974) point of view, the Himalaya is a part of Indian platform, and it may be considered as epiplatformal orogeny. Khain (1984) considers the Himalaya as a typical folded orogeny of Alpine type with geosynclinal stages of evolution and regards it as epigeosynclinal type. However, it is known that this mountain country is a result of a common tectonic regime. Therefore, we consider it in the present study as a continuous first-rank territorial unit.

In general, the relief of the Himalaya is characterized by the presence of a continuous central axis, the flanks of which are deeply dissected by transverse river valleys and complicated by longitudinal valleys, isolated frontal ridges, intermontane basins and plateaus. Orientation of ridge axis and footline of the Himalayan range gradually changes from E–W direction in its central part, to NW–SE in the western part, and to NE–SW in the eastern part. The range is sharply asymmetrical, and its southern flank is much steeper than the northern one (figures 1 and 2).

3.1 *First rank lineaments*

The Himalayan range is separated from adjoining areas by first-rank morphostructural lineaments. Longitudinal first-rank lineaments separate this mountain country from the vast Indo-Gangetic accumulative plains in the south and from the Tibetan highland in the north. Transverse first-rank lineaments separate the Himalaya from Burma Ranges in the east and the Hindukush mountain chains in the west. The different segments within the lineaments are further described with reference to the numbers given to the knots, from west to east (figure 3).

The longitudinal lineament 1–93 at the northern boundary limited by knot 1 in the west and 93 in the east corresponds to a complex deep-seated fault known as Indus-Tsangpo Suture Zone. This zone, characterized by numerous outcrops of
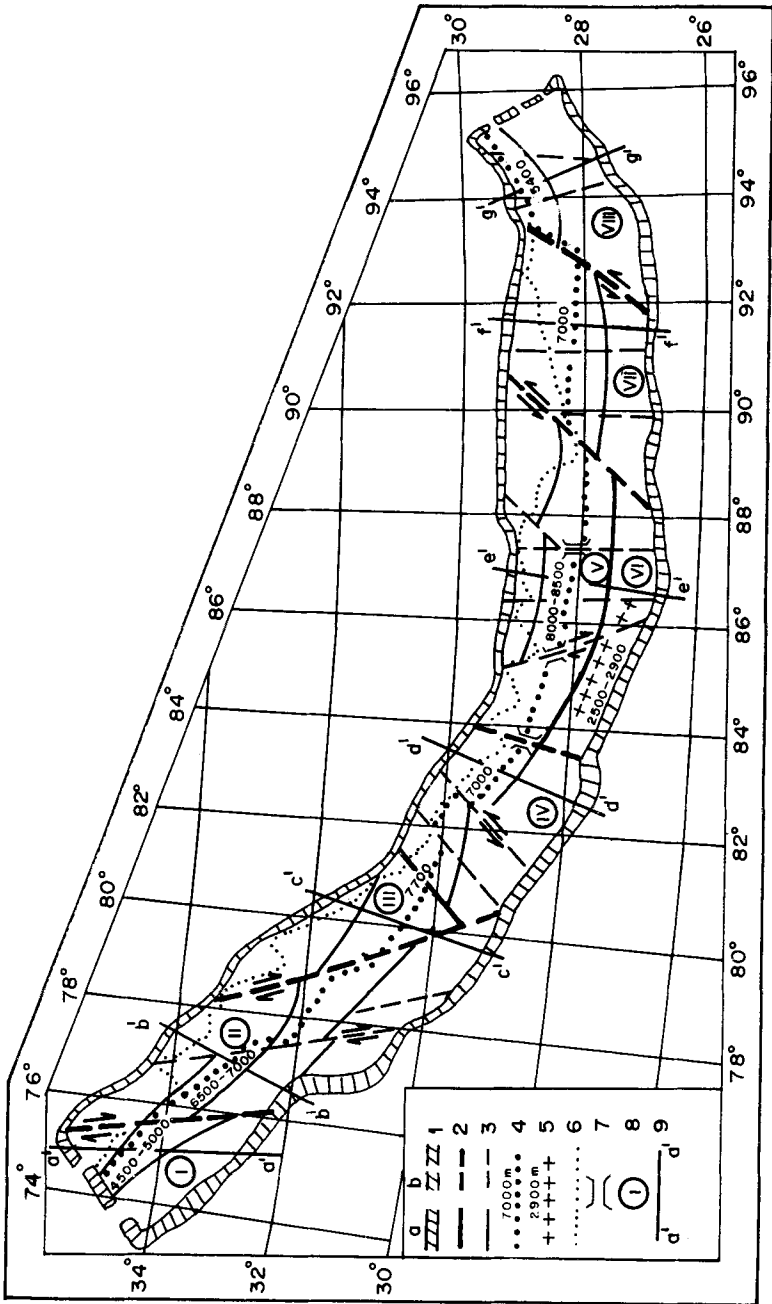
1-3. MORPHOSTRUCTURAL LINEAMENTS, (a)LONGITUDINAL, (b)TRANSVERSE,   FIRST, SECOND AND THIRD RANK
RESPECTIVELY.

4. AXIS AND ALTITUDE OF THE HIMALAYAN RANGE,   5. FRONTAL RIDGE,   6. MAIN WATER DIVIDE

7. ANTECEDENT STREAM SEGMENTS, 8. NUMBER OF MEGABLOCKS, 9. LOCATION OF PROFILES.

Figure 1. Morphostructural zoning map of the Himalaya, showing the block structure.

Figure 2. Topographic profiles in different megablocks.
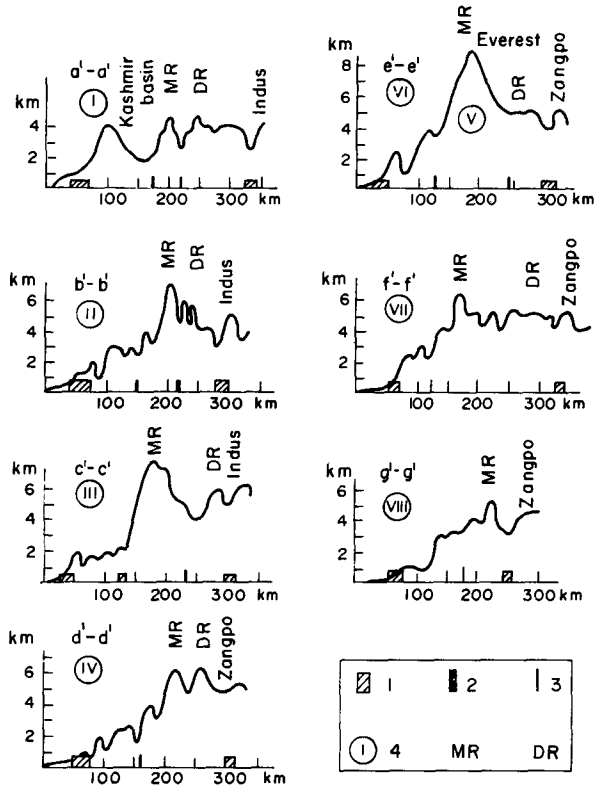
1–3 Location of First, Second and Third rank lineaments respectively
4 Numbers of Megablocks
MR Main Himalaya Range
DR Divide Range

ophiolites, is considered usually as a boundary between Indian and Eurasian plates (Valdia 1984; Windley 1988). The southern boundary lineament 5–96, is characterized by a very complicated inner structure. This zone of lineament includes two systems of subparallel faults namely Himalayan Frontal Thrust in the south and Main Boundary Thrust (MBT) in the north. The former lies between the foothills and the accumulative plains, while the latter separates foothills and mountain slope. The width of lineament zone varies from 10 to 35 km. The segments of the lineament 5–18, 37–56 and 86–89 show maximum width. Along these segments, the mountain slope conjuncts with a broad strip of foothills suggesting that tectonic movements along these segments during orogenic period were not of considerable magnitude. The narrowing of strip of the foothills within the segments 18–37 and 56–86 suggests an increase in magnitude of tectonic movements within them during the Quarternary time.

Western boundary lineament 1–5, corresponds to a northeast oriented thrust (Valdia 1984). Eastern boundary lineament 93–96, is traced in accordance with a system of subparallel faults along the Mishmi Thrust.

1-3. MORPHOSTRUCTURAL LINEAMENTS, (a) LONGITUDINAL, (b) TRANSVERSE
OF FIRST, SECOND AND THIRD RANK RESPECTIVELY.

4. NUMBERS OF KNOTS

5. KNOTS RECOGNIZED AS SEISMICALLY POTENTIAL FOR M ⩾ 6·5

6. EPICENTERS (M ⩾ 6·5)

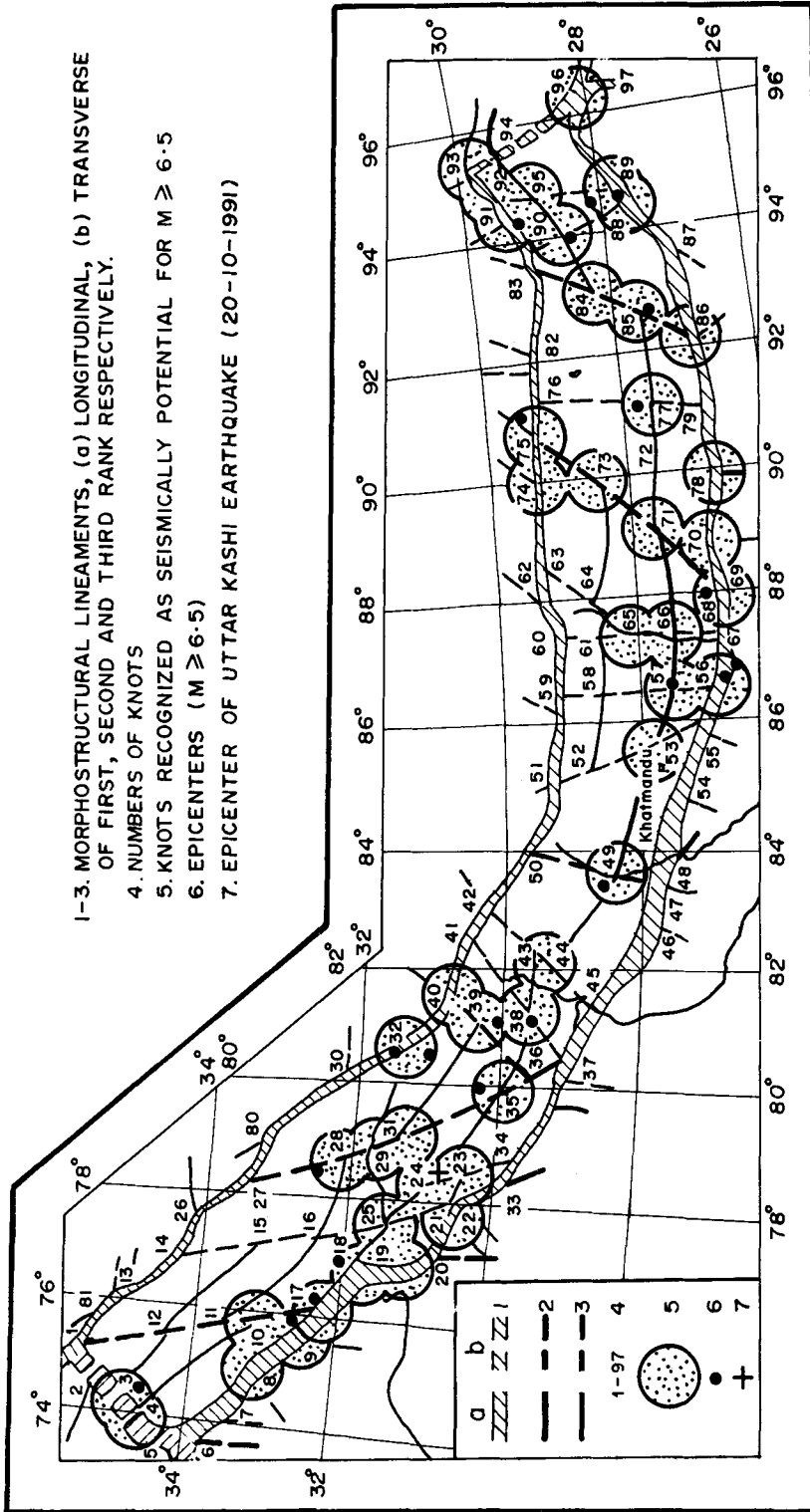7. EPICENTER OF UTTAR KASHI EARTHQUAKE (20-10-1991)

Figure 3. Map showing the locations of potential knots for earthquakes of $M \geq 6.5$.

3.2 *Second-rank lineaments*

Lineaments of second rank form boundaries of megablocks and are represented mainly by transverse lineaments. There is only one second rank longitudinal lineament mapped as the boundary between megablocks V and VI. Zones of transverse lineaments are mostly represented by rectilinear segments of river valleys extending in a common strike, transverse escarpments and along segments of known geological faults. Altitude and strike of the Himalayan range are sharply and considerably changed across the zones of transverse lineaments. Besides, axis and footline of the Himalayan range are also displaced by transverse lineaments.

3.3 *Megablocks*

The Himalayas are subdivided into 8 megablocks in accordance with the changes in altitude and strike of the main axis (figure 1). Their formalized characteristics are given in table 1. These megablocks show different drainage-pattern and have varying shapes of topographic profiles (figure 2). Such different shapes of profiles may be related to the variations of stress-pattern along the Himalayan range. The details of each megablock are described below.

In megablock I, the altitude of the Himalayan range is gradually lowered in an E–W direction from 5000 m to 4500 m. However, the frontal ridge, the water divide and the axial range exhibit the same altitude. This implies a homogeneity in the deformation pattern within the block. The presence of a large intermontane Kashmir basin is distinct in this megablock from other ones.

In megablock II, the Himalayan range axis is oriented in a NW direction with an average altitude of 6500 m. The axis attains its greatest altitude at the western and eastern margins of this megablock. The northern Himalayan flank inside the megablock is extremely short and steep and the width of the block increases to 170 km in the southern flank. The altitude of the Himalayan range suddenly increases to 7700–7800 m within the megablock III and its axis is displaced to the south by a considerable distance.

Table 1. Features of megablocks.

N of megablock	Average altitude of the Himalayan range axis (*m*)	Strike of the Himalayan range axis	Regular changing of the Himalayan range of altitude
I	4500–5000	WNW–ESE	←
II	6500–7000	NW–SE	→
III	7700	WNW–ESE	↔
IV	7000	WNW–ESE	↔
V	8000–8500	W–E	→ ←
VI	does not include Himalayan Range		→ ←
VII	7000	W–E	←
VIII	5400	NE–SW	→ ←

Note: →–trend of increase of the Himalayan Range altitude within megablock.

To the east of Kali river, in megablock IV, the Himalayan range is lowered up to an elevation of 7000 m and maintains WNW orientation. Unlike others, this mega-block consists of a large longitudinal valley developed between the Kali river and Kali-Gandak river. A large ridge is seen extending parallel to the Himalayan range south of this valley. The southern Himalayan flank in this megablock is 4 times larger in area than that of the northern flank.

Megablock V occupies a central and highly elevated part of the Himalaya along with a wide plateau on its northern flank. The Himalayan axis in this block is shifted to south and the orientation becomes east–west. Its altitude attains a maximum of 8000–8800 m which is significantly the highest on the earth.

Megablock VI, located in the southern flank south of Mount Everest, is charac-terized by a combination of frontal ridge of 2900 m elevation and a well-developed longitudinal valley. Frontal ridge is separated from the Himalayan range by Son Kosi valley and a large intermontane depression is located, west of Kathmandu.

In megablock VII, the Himalayan axis is shifted to north and its altitude goes down to 7000 m. The southern flank is relatively very narrow inside this megablock when compared to others. A vast plateau occurs in the northern flank.

In megablock VIII, the Himalayan axis is shifted further to north and is oriented in the NE direction. Its altitude sharply decreases to 5400 m.

3.4 *Third-rank lineaments and blocks*

The third rank longitudinal lineaments divide the Himalaya into blocks according to their tectonic regionalization. They separate the Higher Himalaya (axial part of the Himalayan range) from the Lower Himalaya comprising lower part of the southern flank. The Tethys Himalaya represented by plateau-like surface in the northern flank are further separated by another set of third-rank lineaments. These zones of third-rank lineaments include systems of large thrusts separating main tectonic units of the Himalaya.

Third-rank transverse lineaments are drawn connecting the points of change in the altitude and orientation of axes of Himalayan range. Many of them coincide with the known geological faults (Olta and Akiba 1973; Ganser 1983; Valdia 1976) as well as with some of the lineaments identified from satellite imagery (Mukhopadhyay 1984; Dasgupta *et al* 1987).

In summary, the morphostructural study presents a network of lineaments and a hierarchical system of territorial units in the region of Himalaya. Such a scheme of MSZ for the Himalaya may be considered as a model of recent block mosaic of the area. Relative displacement and interaction of different blocks of various ranks are perhaps the causative sources for the seismicity in the region.

4. MSZ-scheme and seismicity of the Himalaya

The Himalaya is characterized by a high level of seismicity. About 23 earthquakes with $M \geqslant 6.5$ based on the NOAA and Indian Meteorological Department Catalogues (table 2) are considered. The plot of these earthquakes with MSZ-scheme has shown that their epicenters are clustered around intersections of lineaments (knots) within a distance not greater than 50 km (figure 3). It is generally speculated that future

Table 2. Shallow earthquakes of Himalaya region with
$M \geq 6.5$.

No.	Date	Coordinates $\varphi(N)$	$\lambda(E)$	M	N of nearest knot
1	26.08.1833	27·50	86·50	7·5	57
2	18·05.1852	27·00	88·00	6·5	68
3	30.05.1885	34·60	74·38	7·0	4
4	04.04.1905	32·30	76·25	8·0	17
5	28.02.1906	32·00	77·00	7·0	18
6	14.10.1911	31·00	80·50	6·8	32
7	03.02.1915	29·50	91·50	7·1	75
8	28.08.1916	30·00	81·00	7·5	39
9	27.05.1936	28·50	83·50	7·0	49
10	04.06.1945	30·30	80·00	6·5	35
11	22.06.1945	32·60	75·90	6·5	9
12	29.07.1947	28·80	93·70	7·7	90
13	16.08.1950	27·48	92·64	6·7	85
14	18.11.1950	27·73	94·59	6·7	88
15	12.03.1951	28·19	94·49	6·5	89
16	22.04.1951	29·21	94·30	6·5	91
17	23.02.1954	27·80	91·07	6·5	77
18	04.09.1954	28·30	83·08	6·7	49
19	29.07.1960	26·90	90·30	6·5	78
20	06.03.1966	31·50	80·50	6·5	32
21	19.01.1975	32·45	78·43	6·8	28
22	29.07.1980	29·59	81·09	6·6	38
23	20.08.1988	26·78	86·61	6·5	56

earthquakes with $M \geqslant 6·5$ are most likely to occur only within the knots identified from the MSZ-scheme.

5. Pattern recognition approach

Pattern recognition approach can be applied to delineate earthquake prone areas on a set of objects derived from the morphostructural zoning scheme of the region. The objects are described by using a set of parameters. Three broad types of parameters are generally used including geomorphological, geological and geophysical. These features are obtained from a circular area around the knot with a radius of 50 km considered comparable to the influence of an earthquake of magnitude 6·5.

Pattern recognition algorithm "Cora-3" (Gelfand *et al* 1972) with learning stage is applied in our study. The algorithm on the basis of learning set can distinguish the seismically potential zones (D) and non-potential zones (N). However, during the learning stage a knot is considered to be of class D_0 if an earthquake with $M \geqslant 6·5$ had occurred during the past history within that knot. In case of absence of earthquakes of $M \geqslant 6·5$ within the knots, they are considered as class N_0. Characteristic features of these two classes are derived from the learning material and appropriate recognition rules are formulated. These recognition rules are then used to classify all

the knots into either class D (potential) or class N (non-potential) indicating the zones of earthquake potential areas for $M \geqslant 6\cdot5$.

We now introduce some definitions of symbols that are used in this algorithm.

- W to be the general set of objects of recognition.
- $W_0 = (D_0, N_0)$ to be the learning material $D_0, N_0 \subseteq \cdot W, D_0$ corresponds to potential and N_0 corresponds to non-potential objects.
- $\Pi: W = D|-|N$ to be a classification of W with algorithm Π i.e. $\Pi: W = D|-|N$ to be a division of W into two subsets D and N such that $D \cup N = W$ and $D \cap N = 0$.
- $B_p = \{0, 1\}^p$ to be the binary space of p dimensions.
- $D: W \rightarrow B_p$ to be the binary description of objects, for each $w \in W$ d$(w) = \omega = (\omega_1, \ldots \omega_i, \ldots \omega_p)$.

The algorithm CORA-3 characterize the D- objects and N- objects by *features*, that is to say by some combination of values of the components of the binary vector representing the object in B- space. This is a way to represent the joint occurrence of some physical properties and the features are defined in the form of a matrix:

$$T = \begin{vmatrix} i_1 & i_2 & i_3 \\ \alpha_1 & \alpha_2 & \alpha_3 \end{vmatrix}$$

where $i_r = 1, 2, \ldots, p$; $\alpha_r = 0$ or 1; $r = 1, 2, 3$.

An object $w \in W$ possesses the feature T if $\omega_{i_r} = \alpha_r$ for its description d(w) in binary space B_p. Let $K_{D_0}(T)$ be the number of objects of class D in W_0 and $K_{N_0}(T)$ number of objects of class N containing the same feature. Let $K_D, \tilde{K}_D, K_N, \tilde{K}_N$ be some fixed free integers. The feature T is considered to be a characteristic D-feature if

$$K_{D_0}(T) \geqslant K_D \text{ and } K_{N_0}(T) \leqslant \tilde{K}_D.$$

It is a characteristic N-feature if

$$K_{N_0}(T) \geqslant K_N \text{ and } K_{D_0}(T) \leqslant \tilde{K}_N.$$

For each $w \in W$ we define $\Delta(w) = N_D(w) - N_N(w)$ where $N_x(w)$ is number of features which appear in the object w. Let Δ_t be an additional free parameter. The classification

$$C(W_0, K_D, \tilde{K}_D, K_N, \tilde{K}_N, \Delta_t): W = D \cup N \text{ is defined as}$$

$$D = \{w \in W : \Delta(w) \geqslant \Delta_t\}$$

$$N = \{w \in W : \Delta(w) < \Delta_t\}$$

6. Recognition of earthquake-prone areas in the Himalaya ($M \geqslant 6\cdot5$)

In total, 97 knots were obtained from the study of morphostructural zoning. The objective of the study is to classify them into two classes: potential (D) non-potential (N) for earthquakes of $M \geqslant 6\cdot5$.

Among the knots 21 of them are found to be associated with the earthquake epicenters and they are regarded as learning set D_0 for D-class. The knots are: 4, 9, 17, 18, 28, 32, 35, 38, 39, 49, 56, 57, 68, 75, 77, 78, 85, 88, 89, 90 and 91.

Earthquakes with $6\cdot0 \leqslant M \leqslant 6\cdot4$ are known to occur in the knots namely 3, 10, 11,

Table 3. Parameters used for describing objects and thresholds for discretization ($M \geqslant 6.5$).

#	Name of parameter	Thresholds of coding	
		Lower	Upper
1	Minimum altitude in the vicinity of knot, H_{min}, m	< 300	> 2100
2	Difference between maximum and minimum altitudes, ΔH	< 2900	> 4400
3	Gradient of altitudes $\Delta H/l$ (l distance between H_{max} and H_{min} points within the knot	< 40	> 70
4	Combinations of relief types:		
	a) mountain/plain (M/P)	"yes" or "no"	
	b) mountain/piedmont/plain (M/PM/P)	"yes" or "no"	
	c) mountain/piedmont (M/PM)	"yes" or "no"	
	d) mountain/upland (M/U)	"yes" or "no"	
	e) mountain/mountain (M/M)	"yes" or "no"	
5	Distance from the intersection to the nearest lineament of II rank, R_2, km	< 50	> 120
6	Distance from intersection to the nearest intersection, R_{int}, km	< 50	> 62

15, 36, 42, 54, 67, 71, 76 and 86. These were regarded as class under examination. The other remaining 65 knots were put into learning set (N_0) for N-class.

6.1 *Parameters of the objects*

For the purpose of classification the objects are described by parameters from morphology and MSZ-scheme. They are listed in table 3. These parameters represent indirectly the contrast and intensity of neotectonic movements as well as tectonic parcelling in the vicinities of the knots. Numerical values of the parameters were measured from topomaps and MSZ-scheme within a 50 km radius around the knot in accordance with the criteria given in Gvishiani *et al* 1988.

Informativity of each parameter was evaluated on the basis of their one-dimensional distributions (Gvishiani *et al* 1988). The following parameters were found most informative to divide D_0- and N_0- objects: H_{min}, ΔH, $\Delta H/l$, combinations of landforms, R_2 and R_{int} (see table 3).

6.2 *Discretization and coding*

The parameters of the objects were discretized and the objects were coded by two bits. The thresholds of coding are also given in table 3. As a result all objects of recognition were represented by 12-components binary vectors.

6.3 *Learning stage*

On the basis of learning set two sets of features which are characteristic for D_0- and N_0- classes respectively were selected by "CORA-3" algorithm. These are given in

Table 4. Characteristic D-features and N-features for $M \geqslant 6.5$.

#	Combination of relief types	R_{int} km	R_2 km	ΔH m	$\Delta H/l$	H_{min} m
D-features						
1					< 70	300–2100
2			< 50			300–2100
3			< 120		> 70	< 2100
4			> 120		< 70	< 2100
5	"yes":M/P, M/PM/P, M/PM				> 40	
6			< 50		> 40	< 2100
7			< 50		> 70	
8		< 62	< 50			> 300
9		< 62	< 50		> 40	
10		< 62	< 120	> 4400		
11		> 50	> 50	> 4400		
12		50–62		> 4400		
N-features						
1					< 70	> 2100
2			> 50			> 2100
3				< 2900	< 40	
4			< 120		< 40	
5		> 50			< 40	
6		> 50		< 2900	< 70	
7	"no":M/P, M/PM/P		> 120		> 40	
8	"yes":M/M or M/U		> 50	< 4400		
9	"yes":M/M or M/U		> 120			

table 4. The following thresholds for selection and rejection were used for the selection of characteristic features:

$$K_D = 5, \ \widetilde{K}_D = 6, \ K_N = 16, \ \widetilde{K}_N = 1$$

6.4 The recognition stage

The objects from learning and examination sets were classified according to the following rule. An object was assigned to D-class if voting $(N_D - N_N)$ was greater or equal to 0, otherwise assigned to class N. As a result all 21 objects originally from D_0 were classified as potential. Three objects (10, 71, 86) from the class under examination and 24 objects from N_0 were also recognized as potential. In total, 48 objects among 97 defined in the Himalaya were recognized as potential for the occurrence of earthquakes of $M \geqslant 6.5$. Their locations are shown in figure 3.

6.5 Evaluation of the classification reliability

With a view to determine the reliability and stability of our results the following two control experiments are carried out:

1. *"Seismic Future" (SF) experiment*: This experiment is an attempt to repeat the established classification $W = D\mu N$, using the resultant sets D and N as the new learning sets instead of D_0 and N_0. It is generally considered that this experiment is

successful if less than 5% of the total number of objects are classified in the experiment differently when compared with their source classification. In the present study only 4 objects (from 97) changed their classification (less then 5%). The following thresholds of selection and contradiction of "CORA-3" algorithm are used:

$$K_D = 6, \ \tilde{K}_D = 1, \ K_N = 10, \ \tilde{K}_N = 1.$$

The "physical" idea of SF experiment is rather obvious and natural. We assume that sets D and N are well established. Therefore, strong earthquakes are likely to occur around the objects $\omega^i \in D$ in future. Thus we shall have a new learning set $D'_0 = D$. However, if our classification is valid then change in the learning material should not change the result of classification. We consider consistent results of SF experiment as a necessary condition for the confirmation of classification.

2. *"Sliding Control"* (SC) *experiment*: It is designed for establishing classifications on the basis of the learning sets (D_0/w^i) and $(N_0/w^{n_1 + i})$, $i = 1, 2, \ldots, \max(n_1, n_2)$ to check whether classification of the objects belonging to the learning set is stable or not, while they are excluded from the learning set.

The first variant discards the objects $w^1 \in D_0$ and $w^{n_1 + 1} \in N_0$, the second variant resets them but discards the objects $w^2 \in D_0$ and $w^{n_1 + 2} \in N_0$, etc. If one of the sets D_0 or N_0 (with a smaller number of objects) already completely discarded once, we proceed only with the remaining set. We usually consider SC experiment as successful if not above 10% of objects in each of D_0 and N_0 sets change their classification. In our case the percentage was less than 5.

7. Identification of earthquake-prone areas for $M \geqslant 7.0$

The available catalogues of earthquakes of the Himalayan arc region do not contain adequate number of earthquakes of $M \geqslant 7.0$ (see table 2) to enable formulation of suitable learning set. We therefore use the procedure of transferring of criteria of earthquake prone areas between Andes of Southern America and Himalayas. Detailed description of the procedure is given by Gvishiani *et al* (1988).

Criteria transfer is the use of seismicity criteria, established in recognizing potential knots for the occurrence of earthquakes with $M \geqslant M_0$ in one region, for identifying the similar knots in the other region.

The necessary prerequisite for using criteria transfer is the uniformity of recognition objects in the regions under consideration. Voting procedure is done under criteria transfer for the objects of one region using the seismicity criteria of another region. For this reason in the criteria, which are transferred, discretization thresholds of parameters are replaced with discretization thresholds defined for those same parameters in that region onto which transfer is made.

The criteria of earthquake-prone areas with $M \geqslant 7.0$ of South American Andes (Filimonov *et al* 1989) were obtained from the following set of topographic and geomorphic parameters:

H_{min} – minimum topographic altitude within the knot.
ΔH – difference of maximum and minimum altitudes.
R_1 – the distance to the nearest first rank lineament.
R_2 – the distance to the nearest second rank lineament.
H_r – highest rank of the lineament within the knot.

Table 5. Characteristic D-features and N-features for $M \geqslant 7 \cdot 0$ (after Filimonov *et al.* 1989).

#	Highest rank of lineament	H_{max} m	H_{min} m	R_2 km	R_1 km	ΔH m
			Parameters			
D-features						
1				< 64		> 3300
2			< 600			> 3300
3				< 67	< 67	
4	I or II rank lineament					> 3300
N-features						
1						< 3300
2	not I rank lin.			> 67		< 3900
3		< 3600			> 64	
4				> 64		
5			> 600	> 67		
6	I rank lineament		> 600	> 64		

Table 5 gives the features of D- and N-classes. An object is considered to belong to class D if the voting $(N_D - N_N) \geqslant 1$, otherwise to class N. Using this recognition rule the following 36 Himalaya objects were classified as non-potentially for $M \geqslant 7 \cdot 0$ (see figure 4): 4, 6, 8, 9, 10, 17, 18, 23, 25, 28, 29, 31, 35, 39, 40, 49, 53, 56, 57, 66, 68, 70, 71, 74, 75, 77, 78, 84, 85, 86, 90, 92, 93, 94, 95, 96.

All the objects associated with known epicenters of earthquakes with $M \geqslant 7 \cdot 0$ (see table 2) were successfully recognized as potential.

8. Discussion and conclusions

From the criteria obtained (table 4), potential (D) knots in the Himalaya are characterized by their small distances to second-rank lineaments $(R_2 < 50\,\text{km or} R_2 < 120\,\text{km})$ and to the nearest intersection (Rint $< 62\,\text{km}$). At the same time D-knots also show a large difference in altitudes $(\Delta H > 4400\,\text{m})$, large values of altitude–gradient and small values of $H_{min}(H_{min} < 2100\,\text{m})$. Besides, combinations of contrasting types of relief such as mountain slope/piedmont plains and mountain slope/piedmont hills/piedmont/plains are predominant features of D-knots. Such a set of characteristic features around D-knots indicate a high level of tectonic parcelling and intense neotectonic movements in the vicinity of such knots. Criteria of non-potential (N) knots consisting of the same parameters reveal different values pointing to a lesser degree of tectonic activity around non-potential knots.

Along the Himalaya, majority of D-knots are located on the first-rank lineament at the southern boundary and along the transverse second-rank lineaments. D-knots are mostly concentrated along a few segments at the southern boundary lineament. The knots including 6, 8, 9, 17, 18, 19 and 21 occupy western segment of the lineament where its strike is sharply reoriented in north-west direction and shifting of Himalayan range to north takes place. The other group of knots namely 56, 68, 70 and 78 is
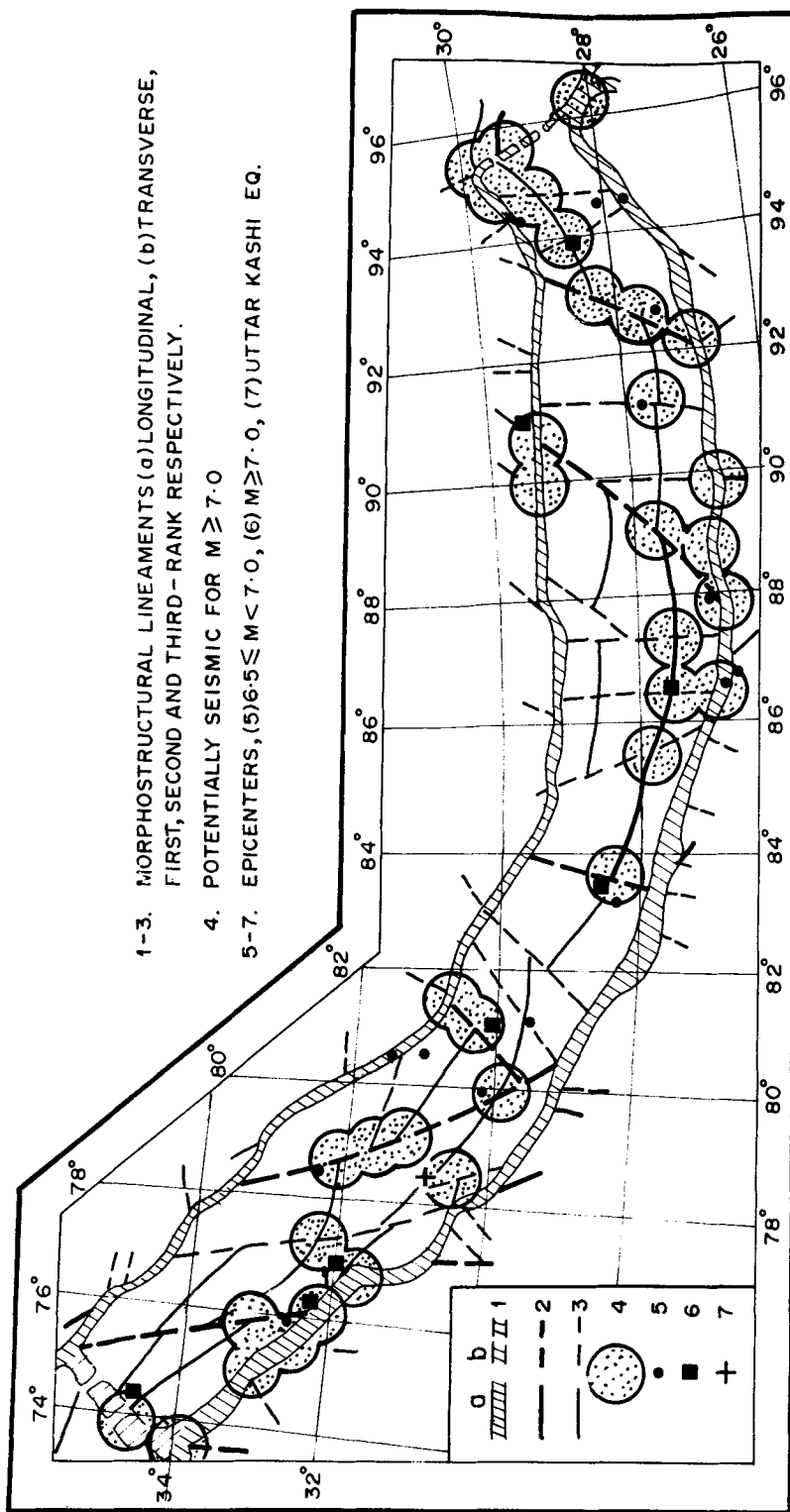
Figure 4. Map showing the locations of potential knots for earthquakes of $M \geq 7.0$.

located in the central part of the lineament where piedmont hills disappear, and the junction between mountain slope and accumulative plains is very sharp because of neotectonic movements. The third group of knots namely 86, 88, 89 and 96 is located on the eastern part of lineament, where its strike changes from east-west to north-east and shifting of the Himalayan belt to north. Only seven knots (32, 40, 74, 75, 91, 92, 93) on the northern boundary of Himalayas were recognised to be potential. The northern boundary seems to be less earthquake prone as compared with the southern boundary.

The results of pattern recognition reveal that almost 50% of knots in the Himalayan belt are found to be potential for earthquakes of magnitude $M \geqslant 6.5$. Taking into account the high level of seismicity of the region and positive results of the control experiments, the obtained classification might be considered reliable. The results of this classification were presented earlier, in the symposium on 'Earthquake Prediction held at Strasbourg, France in March 1991 (Gorshkov et al 1991). It is interesting to note the occurrence of earthquake of $M = 6.6$ on 19th October 1991 in the western part of the Himalaya near Uttarkashi. Epicenter of Uttarkashi earthquake is located within the knot 24 which has been recognized as potential for $M \geqslant 6.5$ (see figure 3). The study for $M \geqslant 7.0$ reduces the number of potential knots from 48 to 36 (figure 4). The knot no. 24 associated with Uttarkashi earthquake is recognised as potential in this study as well. It is also significant to note that strong earthquakes in this area were not known earlier.

The areas indicated in figures 3 and 4 provide a possible model of the potential zones for the occurrence of strong earthquake in the Himalayan arc region and could be of much help in defining seismic hazard in the region.

Acknowledgements

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