RECOGNITION OF EARTHQUAKE-PRONE AREA (M ≥ 5.0) APPLIED FOR NORTH VIETNAM AND ADJACENCY

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Received: February 2, 2012

Abstract

Seismogenic nodes capable of earthquakes with M ≥ 5.0 have been identified in the Northern Vietnam that exhibit the highest seismic activity over the Vietnam territory. Recognition objects - morphostructural nodes - have been delineated with the morphostructural zoning (MZ) method and their classification into seismogenic nodes and non-seismogenic ones was performed with the pattern-recognition.

With MZ we have compiled a morphostructural map (scale 1:1,000,000) for the study region. The map shows the hierarchical block-structure of the region, the network of boundary zones bounding blocks, and the loci of the nodes. A three-level hierarchy has been established for the blocks and their boundaries. The recorded M ≥ 5.0 earthquakes nucleate at the nodes delineated by MZ, i.e. ignoring the seismic record. Among all delineated nodes we recognized the seismogenic ones (D), prone to M ≥ 5.0 earthquakes, with the pattern recognition algorithm CORA-3. The performed recognition pinpoints a number of D nodes where events with *M* ≥ 5.0 have not been recorded to date.

Key words: North Vietnam, Morphostructural zoning, Pattern recognition, Seismogenic nodes

1. Introduction

The identification of prone areas to M ≥ 5.0 earthquakes in North Vietnam has been carried out applying the morphostructural zoning (MZ) method which proposed by [1, 8, 9], to delineate morphostructural nodes, i.e. specific structures formed at the intersections of fault zones. Pattern recognition algorithm CORA-3 [4, 8] has been used to select the nodes with significant seismogenic potential.

The fact that earthquakes nucleate at nodes was first established for the Pamirs and Tien Shan regions [4]. The roles of intersecting faults are observed in different tectonic settings. Talwani found that large intra-plate earthquakes are related to intersections and demonstrated [20, 21] that intersecting faults provide a location for stress accumulation. Hudnut et al. and etc [15] observed the relationship between earthquakes and intersections for plate boundaries and rift structures, respectively. According to King [16], fault intersections provide locations for initiation and healing of ruptures. A model proposed by Gabrielov et al. [3] implies that block interaction along intersecting faults leads to stress and strain accumulation and secondary faulting about the intersection. This causes generation of new faults of progressively smaller size, so that a hierarchical mosaic structure, essentially, a node, is formed about the intersection.

The methodology has been previously applied in many seismic regions of the world [2, 4-12]. Recent earthquakes in each of the studied regions ensure the reliability of the methodology. As Gorshkov et al. demonstrated, 90% of the post-publication events with relevant magnitudes occurred at the nodes, and 84% of the post-publication events occurred at the nodes recognized as prone to large earthquakes [8].

2. Methodology

Two principal steps compose the methodology. The first step is the delineation of the objects of the analysis - the morphostructural nodes - by the morphostructural zoning (MZ) method. The second is the classification of all mapped nodes, by the pattern recognition algorithm CORA-3, into nodes where earthquakes with magnitude exceeding a certain threshold are possible and nodes where only earthquakes with smaller magnitude may happen. Here we describe only the basic definitions necessary for the understanding of the results.

Morphostructural zoning method: By the MZ, a studied region is divided into a system of hierarchically ordered areas characterized by homogeneous present-day topography and tectonic structure [1, 8, 19]. MZ distinguishes (1) blocks (areas) of different rank; (2) their boundary zones, morphostructural lineaments; and (3) sites where lineaments intersect, nodes.

Large-scale geostructures e.g., the Alps) [9] developed by a common orogenesis and characterized by uniform orographic appearance are considered the highest first rank units, mountain countries. They are divided into second rank areas, megablocks, which are further subdivided into third rank areas, blocks.

A morphostructural lineament is viewed as a boundary zone between territorial units delineated by MZ (see relevant discussion by Gorshkov et al. 2003) [8]. There are no morphostructural lineaments (from here, lineament) in the absence of a recognized territorial unit (a block). All components of the hierarchical system compose a single system. A morphostructural lineament is viewed as a boundary zone between territorial units delineated by MZ. The rank of the lineament is determined by the rank of a territorial unit bounded by it, according to the hierarchical procedure of MZ. MZ differs from the standard morphostructural analysis [14] where the term "lineament" is used to define the complex of alignments detectable on topographic maps or on satellite images. According to that definition the lineament is locally defined and the existence of the lineament does not depend on the surrounding areas. In MZ, the primary element is the block - a relatively homogeneous area, while the lineament is a secondary element of the morphostructure. The borders of the blocks form the lineaments. This means that the existence and the position of the lineaments are determined not locally, but as a part of a broad pattern. If a certain alignment does not separate two topographically different areas, that alignment cannot be viewed as a lineament in MZ, therefore, the lineaments are secondary features with respect to the blocks.

The rank of the lineament depends on the rank of the area limited by the lineament. With respect to the regional trend of the tectonic structure and topography, two types of boundary zones are distinguished: (1) longitudinal and (2) transverse lineaments. Longitudinal lineaments are approximately parallel to the regional strike of the tectonic structure and of the topography and, as a rule, include the prominent faults. In general, they are more evident than transverse lineaments. Transverse lineaments go across the regional trend of the tectonic structure and of the topography. Normally, they appear on the Earth's surface discontinuously and are represented by escarpments, by rectilinear parts of river valleys, and partly by faults. Higher rank lineaments include the wider zone of deep-seated deformation. For instance, Gvishiani et al. [12] for the Caucasus and Cisternas et al. [2] for the Western Alps demonstrated that first and second rank lineaments can be associated with considerable changes in the thickness and in the configuration of Moho discontinuity, while third rank lineaments correspond to the escarpments in the crystalline basement.

A real size of the lineament zone can be mapped from fieldwork; according to our experience, the width of the first rank lineaments, for example, varies from 5 - 8km to 25 - 30km [11, 12, 19]. Additionally, the width of this complex zone may vary along a given lineament.

Morphostructural nodes (from here on, nodes) are formed around the intersections or junctions of two or more lineaments. A node may include more than one intersection or junction. Lineament zones become wider at nodes. Nodes are characterized by a mosaic combination of various topographic forms and by an increased number of linear topographic forms of various strikes that reveal the instability of the area. River valleys within the nodes are represented by a sequence of rectilinear segments that are often shifted with respect to each other. Knee-like bends are characteristic of the river courses at a node. In the vicinity of nodes, tectonic faults branch and/or become bent; sometimes a fault system with one orientation merges into a fault system with another orientation.

Pattern recognition applied to identification of earthquake-prone areas: The use of the pattern recognition approach suggests that nodes already marked by one or more strong earthquakes might have a similar portrayal that can be used to identify nodes, which did not yet explicitly show up as earthquake-prone. The goal of the recognition is to classify all the nodes delineated within a region into two classes:

(1) Class D containing the nodes where earthquakes with magnitude $M \geq M_0$ may occur;

(2) Class N containing the nodes where only earthquakes with $M < M_0$ may occur.

Nodes are characterized by a set of topographic, geological and geophysical parameters. A vector of values of these parameters represents each node. The set of these vectors is the input for the CORA-3 pattern recognition algorithm [5, 8, 12] that is used in this work.

Application of the CORA-3 algorithm consists of the following two stages:

(1) Learning stage - selection of the distinctive features of each class on the basis of the training set composed by D_0 and N_0 subsets, which are constituted by all the sample nodes representative of the classes D and N, respectively;

(2) Classification stage - determination of the class to which each node belongs.

The distinctive features (characteristic traits) for classes D and N are selected at the learning stage as follows.

Let l be the number of components of the binary vectors representing the node. The trait is a matrix **A** defined as:

$$\mathbf{A} = \begin{Vmatrix} i_1 & i_2 & i_3 \\ \delta_1 & \delta_2 & \delta_3 \end{Vmatrix},$$

where i_1, i_2, i_3 are natural numbers, such that $1 \leq i_1 \leq i_2 \leq i_3 \leq l$ and δ_1, δ_2, δ_3 are equal to 0 or to 1. A node (binary vector) numbered i, $\omega^i = (\omega_1^i, \omega_2^i, ..., \omega_l^i)$ posses the trait **A** if $\omega_{i_1}^i = \delta_1,\ \ \omega_{i_2}^i = \delta_2,\ \ \omega_{i_3}^i = \delta_3$.

The characteristic traits are selected with four parameters of the algorithm $k_1, \bar{k}_1, k_2, \bar{k}_2$, which must be integer non-negative values. Let W be the set of all the nodes considered and K(W, **A**) the number of nodes $\omega^i \in W$ that posses the trait **A**. The trait **A** is a characteristic trait of class **D,** when K($\mathbf{D_0}$, **A**) $\geq k_1$ and K($\mathbf{N_0}$, **A**) $\leq \bar{k}_1$, and the trait **A** is a characteristic trait of class N, when K(N_0, A) $\geq k_2$ and K(D_0, A) $\leq \bar{k}_2$.

The classification is made as follows. For each node ω^i the algorithm calculates the number n_D^i of the characteristic traits for class D, the number n_N^i of those for class N, and the difference $\Delta_i = n_D^i - n_N^i$. Class D includes the nodes ω^i for which $\Delta_i \geq \Delta$, while class N includes the nodes for which $\Delta_i < \Delta$. Δ as well as $k_1, \bar{k}_1, k_2,$ and $\bar{k}_2$ is a parameter of the algorithm.

3. Tectonic and morphostructural zoning of north Vietnam

3.1. Tectonic and morphological settings

The modern active tectonic period of the study area started from the Late Cretaceous and lasted during Cenozoic (80 m.y. up to now). In the prime of Cenozoic, the study area and Vietnam as well were located in the southeastern margin of the Eurasia plate [25], in the conjunction of three great tectonic plates: the Eurasian, the Indo-Australian and the Pacific. The study area was strongly affected by collision of the Indo-Australian plate to the Eurasian along the Himalayan obduction zone, which influenced the Indochina block from west and northwest, and in addition it was effected by the subduction of the Pacific plate underneath the Eurasian. The consequences of those movements were the southeastward counter clockwise rotation of the Indochina block and the opening of the East Vietnam sea during a period of 17 - 32 m.y. ago.

The present tectonic setting was created by inheritance of the Earth's crust born previously on the basis of the development process of amalgamation, orogenes and migration of the ancient formations. The study area belongs to the North Vietnam as shown in dash-line rectangular in the map, which has a specific tectonic position, on the junction of the South China Block and the Indochina one by the giant Red river fault zone. The fault zone splays from the eastern margin of the Tibet plateau, crossing the study area and spreads to the East Vietnam sea and is characterized by four metamorphic complexes including Xuelong Shan, Diancang Shan, Ailao Shan and Elephant mountains (DNCV) in North Vietnam (*fig. 1*). This fault zone plays important role in the explanation of tectonic development of the study area as a boundary between the South China and the Indochina blocks.

The Cenozoic tectonic framework of Vietnam reflects style of Cenozoic intra-plate orogenic movement with clear blocky-mosaic characteristics (Ngo Gia Thang et al) [22]. This feature also shows the dependence on previously existing basement (of continental type, which had been formed during different tectonic stages) and on the inheritance of Pre-Cenozoic architecture of the tectonic orogenic movements during Cenozoic, particularly on continental and intraslab areas. At the same time, the Cenozoic tectonic activities of the lithosphere continent of North Vietnam were directly and indirectly affected by adjacent dynamic arcs, such as the West Pacific islands and volcanic arcs from the east and the Indonesian islands and volcanic arcs from the south - southwest; the collisions between Indian-Eurasian plates in the Himalayan region from the northwest, and also directly impacted by internal deep movements underneath the lithosphere layer and the continental crust. These tectonic movements have had a long development history from Early Paleozoic to Present.

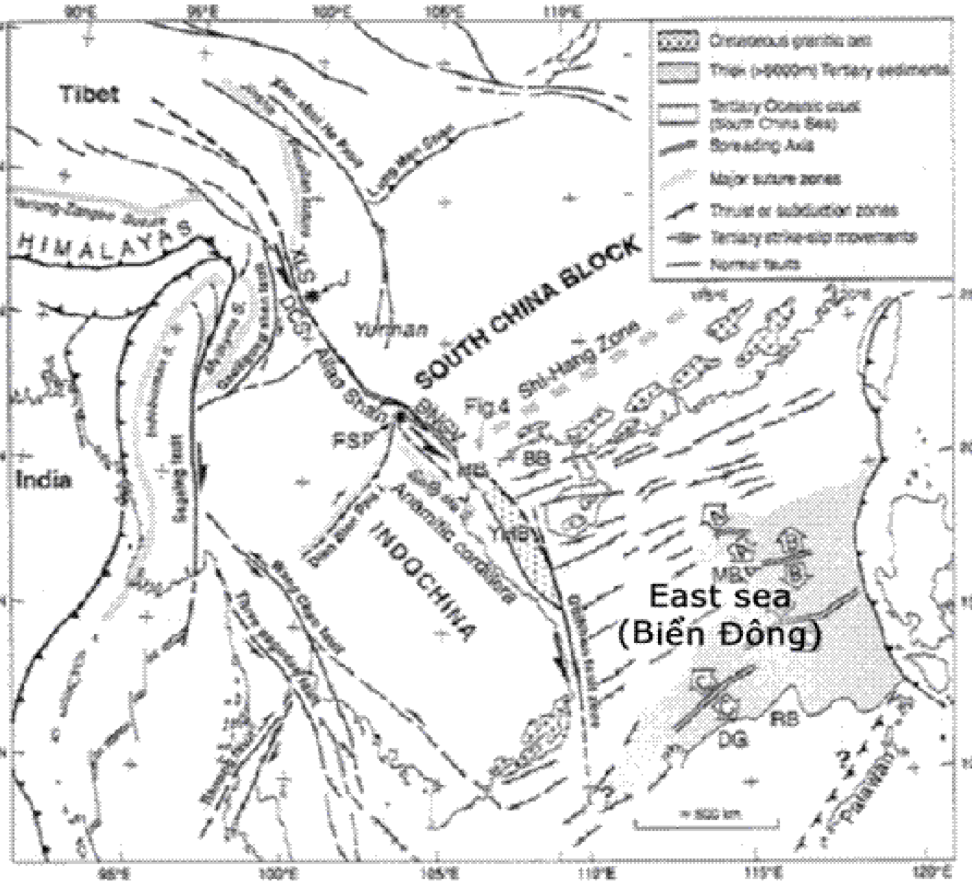

Fig. 1. The skeitch of main faults in Southeast Asia (Modified after P.H. Leloup, 2001)
(Studied area in dash-line rectangular)

A model of Cenozoic tectonic zoning of the North Vietnam clearly reflects the blocky characteristics of the continental lithosphere in the region: the combination of different types of architecture results in blocks - the zones of the heterogeneous Earth's crust with different hierarchy and dimensions, which formed by the Pre-Cenozoic folded basement (*fig. 2*).

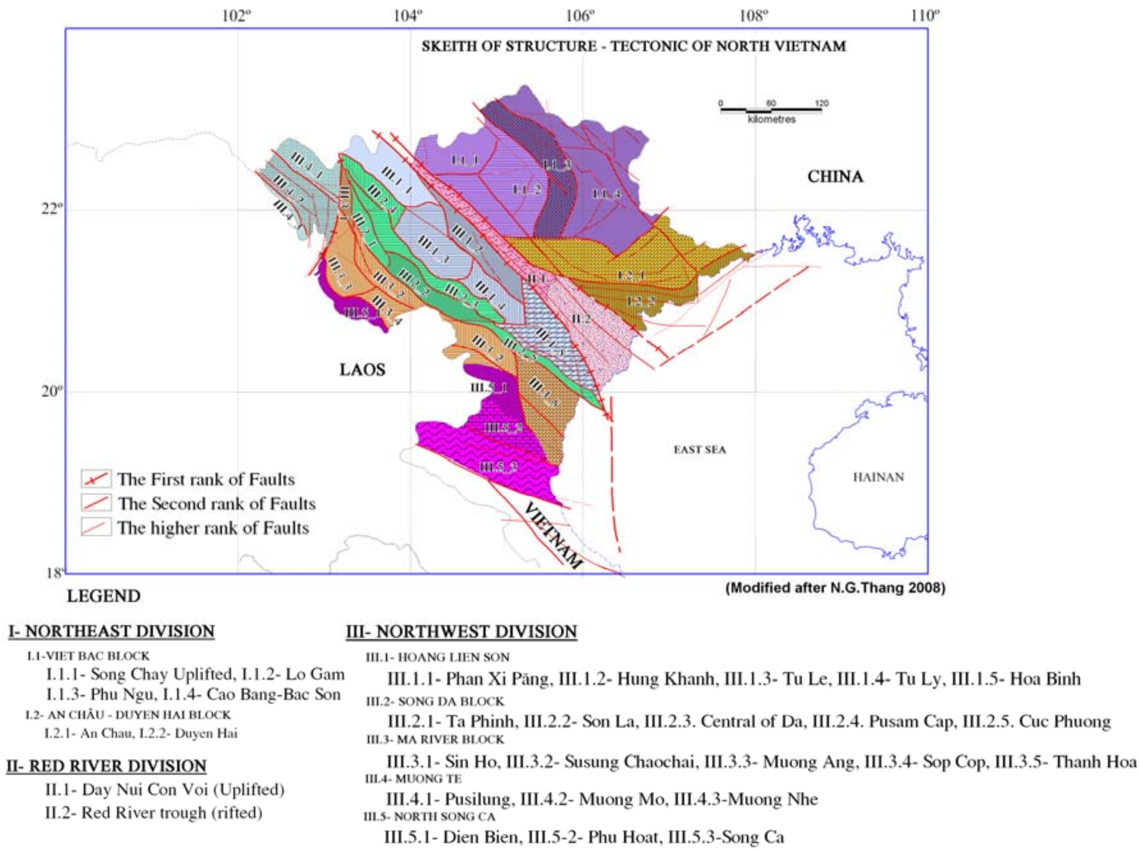

Fig. 2. The skeich of structure-tectonic of North Vietnam (Modified after N.G.Thang [22])

The tectonic deformation took place mainly along the heterogeneity boundaries of the continental crust: where the boundaries of the ancient active zones existed. Therefore, the most important factor to determine the first rank architectures after continental crust is the different folded domains at regional scale, as well as their rates and the type of higher rank structures included within them. This factor controls the movement trends, deformation level and types as well as the morphology of the Cenozoic architectures. The higher elements of the same architecture can be distinguished not only by morphology (they are usually controlled by the morphology of the lower ranked architecture), but also by intensity, severity and types of deformation, as for example uplift or settlement intensity, arc-type or linear uplift, orogenic or rifting process, the level of differentiation,… their material contents and ranking relationships are usually divided by the faults systems of the same rank with evidence of movements during Cenozoic and Present time. On the other hand, it should be emphasized that no matter the movements directions are horizontal or vertical ones, they all result in the vertical differentiation of topography and one of the clear evidence of that are the mountains in continents in modern topography. Based on the above mentioned assumptions, we developed a model of Cenozoic tectonic zonation of North Vietnam, which consists of three main divisions: the Northeast, the Northwest with the Red river fault zone in between.

The Northeast Vietnam division: This division has a folded basement which consists of the Pre-Cambrian and Mid-Paleozoic folded architectures that experienced heavy changes during Mesozoic with the Carthazia folded domain. The division is bounded from the southwest by the Red river fault zone and became a subsided continental shelf in the south - southeast part. According to the morphological characteristics of architectural style, amplitude of Neotectonic deformation, deep structures, modern relief and evidence of tectonic activities, this division can be divided into two lower ranked subdivisions: the Viet Bac uplift block of dome shape (the Viet Bac block) on the north which dominated by the uplifting process and the Littoral An Chau linear uplift block (the Littoral An Chau block) with the Thuong river deep-seated fault zone (also known as the 13A highway fault zone) in between. In general the entire Viet Bac block is a dome-shaped uplift block, strongly cut by various faults systems, majority of which are deep-seated ones. These faults systems separate the Pre-Cenozoic structures, which had been reactivated during Cenozoic, into blocks where higher ranked blocks mostly inherit the Pre-Cenozoic structures (Pre-Cambrian, Paleozoic and Mesozoic). The highest uplift amplitude is observed in the northern part of the division, then gradually decreased in the south and southeast directions, coupling with faults systems which separate the lower ranked architectures (of 2nd and 3rd ranks) and formed an arc-shape scheme toward the east and southeast directions. The above mentioned characteristics, as well as the deep structure features make the difference between the Viet Bac block and the Littoral An Chau one.

The Littoral An Chau folded linear uplift block includes: the light-uplifted synclinal An Chau block which superimposed on a Mesozoic depression basin of the same name and the Littoral uplift block which superimposed on an anticline structure of early Paleozoic to Mesozoic age. The An Chau block is prolonged in NE-SW direction, with the western part sharpened by the Red river fault zone. On the regional framework, the structure consists of a set of higher ranked zones, the axes of which are parallel with the main structure's axis, creating a slightly folded portrayal with uplift amplitude exceeding 1000m, such as the Mau Son, the Tam Lang and the Tam Dao uplifts. The marginal part of the block, located next to the Red river delta, is created by uplift zones with lower amplitude, about 200 to 300 m such as the Luc Ngan and the Red river delta depression. Divided by the Cao Bang - Tien Yen fault, the An Chau structure zone has smaller uplift amplitude comparing to the other surrounding structures (about 500m) and belongs to the low - hill morphological type, forming a giant synclinal structure developed upon a Mesozoic depression.

Located in the southern part of the An Chau zone is a anticline dome-shape uplift Duyen Hai (Littoral), which consists of higher ranked domes and troughs. Majority of these structures have axes of latitudinal or sub-latitudinal direction, and those located in the continental shelf have arc shape with their convexes facing southwards. The most typical high-rank structures are: the Yen Tu (or Tan Mai) dome shape uplift with amplitude exceeding 1000 m which superimposes on an Early-Middle Paleozoic folded basement; the Hon Gai synclinal uplift developed on a trough, which aged T3n-r and heavily differentiated by higher ranked faults systems in various directions and the marginal Ha Coi structural zone which was created on a trough of Jurassic age and had been involved in the settlement process during Cenozoic.

In general, the Northeast Vietnam division is performed as large and differentiated uplifted architecture having the Chay river - Phu Tha Ca dome at the top, then sloped gradually and spreading down to the south, southeast directions and sink under the Red River and Loi Chau, Bach Long Vi depression. The common uplift background is complicated by the local subsidence trenches and raising troughs which create a folded - blocks mosaic, clearly inheriting structural framework of the basement.

The Red River Faults zone: In the tectonic framework of the Southeast Asia and particularly of the North Vietnam, the Red river fault zone plays important role in dividing two main Cenozoic tectonic divisions. Based on the morphological characteristics and the tectonic activities evidence, the faults zone can be divided into two parts with belong to the second rank of architecture, namely the dome shaped Con Voi synclinal uplift block occupying the whole territory from the Vietnam - China border to Viet Tri province, with maximal amplitude of 1000 m; and the intraplate Red River trough formed by the graben system of Red River, Lo River faults which shows quite clearly the evidence of the rifting movements.

Morphologically, the Red river trough is a prolonged narrow architecture with the wedge shape at Viet Tri and offshore in the East Vietnam sea and as mentioned above, it is controlled by the normal faults systems. The subsidence amplitude reaches a maximum value of 13km at the center of the Tonkin Gulf, where the sea depth is not exceeding 90m. The internal architecture of the Red River trough has a shaped of graben lowering toward the center direction, created by the system of normal faults of NW-EW direction and reaches the maximal depth in the Dong Quan trough and the Gulf of Tonkin. On the other hand, the expansion of the depression in the central part of the trough is related to the cross-structural faults systems and the radial faults characterized for the Hanoi depression, also known as the negative flower structures.

The manifestation of modern tectonic movements in the zone is characterized by the prevailing subsidence with a rate of more than 2mm/year in the littoral areas, which results in a Pliocene - Quaternary layer (≈5 m.y) with thickness of more than 500m (according to the bore-hole data) and somewhere in the Tonkin Gulf the thickness of the central part of the trough reaches almost over 4000m.

Northwest Vietnam division: The Northwest Vietnam tectonic division is located entirely inside the Indochina geoblock, adjacent to the South China geoblock in the northeast by the Red river faults zone. The division consists of high rank geodynamic blocks such as the Hoang Lien Son, the Da river, the Ma river, the Muong Te, and the North of Ca river blocks.

- The Hoang Lien Son geodynamics block has a dome shape uplifted zone developed in the NW-SE direction and is limited in the northeast side by the Red River faults zone. This is the highest uplift in the whole area with the modern topography of above 3000m and the calculation of average uplift amplitude for the whole Neotectonic stage gives the value of 5000m. The block was developed on the Pre-Cambrian folded basement and strongly reactivated in Mesozoic and Cenozoic times by creation of the Cretaceous volcanic extrusion of Tu Le basin and the Paleogen granitoit intrusive activities. The Hoang Lien Son geodynamics block can be divided into the high rank structures such as the Phan Si Pang, the Tu Le, the Hung Khanh, the Tu Ly, the Hoa Binh and the Kim Boi ones.

- The Da river geodynamic block is located in the southern part of the Hoang Lien Son geodynamics block and is limited by such the main faults as the Phong Tho, the Than Uyen, the Muong La-Bac Yen, the Cho Bo and the Da river ones. The main content of the Da river geodynamics block is of the Da river and Son La tectonic assembly origin and aged Late Triassic. The internal architecture of the block during Cenozoic can be classified to the high rank structures such as the Ta Phinh, the Son La, the Central Da river, the Pu Sam Cap and the Cuc Phuong ones.

- The Ma river geodynamic block is located in the southern part of the Da river geodynamics block and is limited by the main faults systems such as the Tuan Giao, the Ma river and the Dien Bien - Lai Chau ones. This is the zone with highest seismic activity in the Northwest region. The folded basement of this block was created from the different tectonic complexes of Late - Proterozoic to Early - Paleozoic ages such as the Nam Co, the Ma river and the Thanh Hoa ones. The Ma river geodynamics block has undergone the transformation process during the period from Late-Paleozoic to the end of Mesozoic. On the modern tectonic framework, the Ma river geodynamics block can be divided to high rank structural such as the Sin Ho, the Susung Chaochai, the Muong Ang, the Sop Cop and the Thanh Hoa ones.

- The Muong Te geoblock is located in the southwestern part of the Lai Chau - Dien Bien fault, which separates it with the Ma river, the Da river and the Lai Chau geodynamics blocks in the south. The basement of the Muong Te geoblock was formed by the complex tectono-stratigraphic assemblage of Pusilung and Muong Te that had been consolidated during the Indosinia tectonic regime containing the continental-complex deposition of Jurassic Molas, Cretaceous and possibly Paleogen ages. The modern tectonic activities took place in this geoblock is of moderate intensity. The Muong Te geoblock can be divided into the higher ranked geodynamics blocks which developed on the Mesozoic basement such as Pusilung, Muong Mo, and Muong Nhe.

- The North of Ca river geodynamics block is located to the southwest of Ma river block and controlled by the main faults such as the Ma river, the Fumaytun, the Sop Cop, the Quan Son and the Ba Thuoc - Lang Chanh ones. The geodynamics block's basement consists of the Pre-Cambrian to

Late Paleozoic folded complexes and superimposed by the tarfogen Sam Nua - Hoanh Son depression of Triassic and Jura ages and the red molas depressions of Late Triassic and Late Cretaceous ages.

3.2. Morphostructural zoning

The morphostructural map of North Vietnam (*fig. 3*) has been compiled at the scale of 1:1,000,000 on the basis of the combined analysis of topographic and tectonic maps, satellite photos, and relevant publications. The North Vietnam territory includes areas of two large scale tectonic units, namely, the South China Block and Indochina Block. Apart from difference in Neotectonic structure and geologic history, these blocks differ in the recent topography. According to the MZ principles [8], both blocks are assigned to first rank units called mountain countries. These units are divided by the first rank lineament going from 1 to 51 (*fig. 4*) that corresponds to the Red River Fault Zone (RRFZ), which is a major tectonic feature of the South-East Asia. Both mountain countries have been divided into mega-blocks - second rank territorial units (*fig. 3*). Mega-blocks 1 - 3 belong to the Indochina Block and mega-blocks 4 - 6 are delineated within the South China Block.

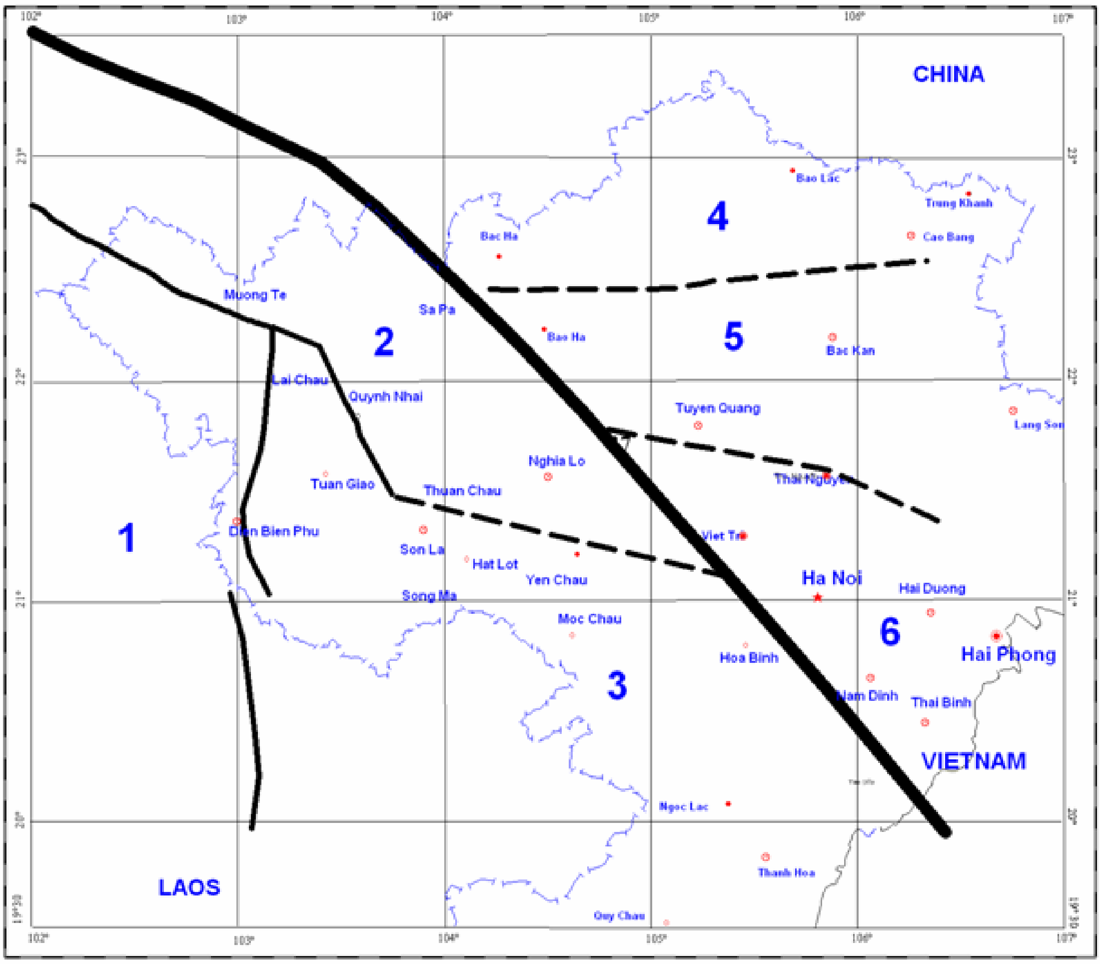

Fig. 3. Mega-blocks in North Vietnam defined with MZ. Thick line marks first rank lineament; Thin lines show 2nd rank lineaments separating of mega-blocks, 1-6 refer to numbers of mega-blocks

Mega-blocks differ in elevation and dominant orientation of ridges composing these mega-blocks. Mega-blocks are divided by second rank lineaments. The longitudinal second rank lineament separating mega-block 1 from mega-block 3 corresponds to the Dien Bien Phu fault.

Transverse second rank lineaments have been defined with MZ. Mega-block 4 includes the elevated plateau within the South China Block. Topography of mega-block 4 is presented by chains of hills oriented in NW-SE direction and divided by rivers of similar strike. Mega-block 6 embraces the flat lowland areas within the Red River delta filled with recent alluvium. Names of mega-blocks: (1) Muong Te, (2) Hoang Lien Son, (3) Northwest region (elevated plateau), (4) Viet Bac (hill chains, transition zone between plateau and RR delta), (5) An Chau - Duyen Hai, (6) Red River Delta.

Mega-blocks have been divided into smaller units, blocks, by third rank lineaments (*fig. 4*). The third rank lineaments control local sharp changes in the altitude of individual ridges composing mega-blocks; they have been traced along elongated scarps and/or rectilinear segments of river valleys that are usually fault-dominated in tectonically active environments [17, 18]. Most of 3-rd rank longitudinal lineaments are also correspond to tectonic faults shown on tectonic map of Vietnam [8]. In total, MZ outlined 134 intersections of lineaments (*fig. 4*) and we consider each of them as a node. These 134 nodes form the set of recognition patterns.

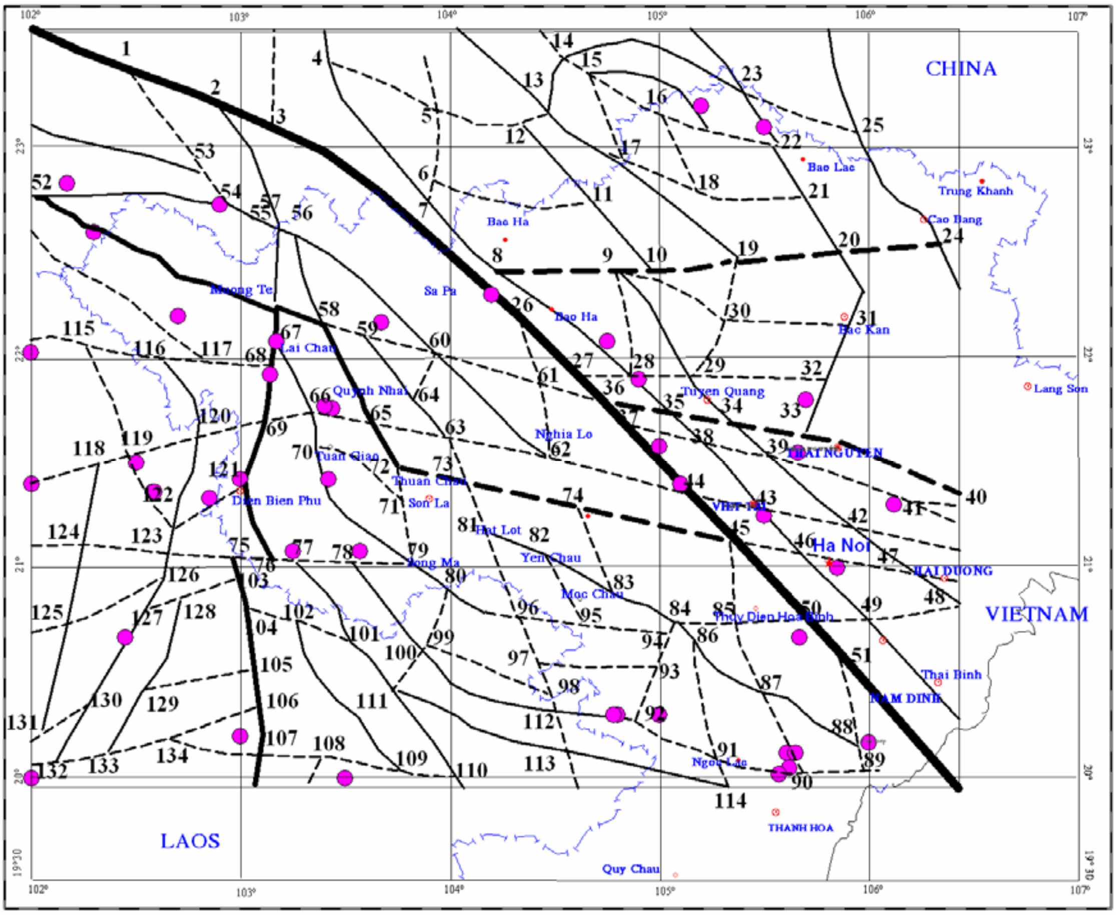

Fig. 4. Morpho-structural map of North Vietnam. Thick lines are the lineaments of the first rank; Medium lines are the lineaments of the second rank; Thin lines are the lineaments of the third rank; Continues lines are the longitudinal lineaments; Discontinuous ones are the transverse lineaments; Rose dots show earthquakes M5+

4. Nodes and earthquakes with magnitude ≥ 5.0

4.1. Seismicity pattern

Within the Northern part of Vietnam's territory, base on analysis the earthquake activities by the distribution rules, as well as targets depth of frequency earthquake hypocenter showed the expression of other distinct activities, well-suited as six sesmogenic zones has been divided by D.T. Hai [13]: VietBac (I), Dong Trieu - Cam Pha (II), Red River (III), Song Da - Song Ma (IV), Muong Te - Dien Bien (V); and Song Ca - Rao Nay (VI). The earthquakes catalogue of studied area updated to the end of 2008 [23, 24] which combined on the base of three data sources as follows: (1) Historical earthquake; (2) Earthquakes investigating in public; and (3) Earthquakes recorded from seismic station network of Vietnam and ISC, NEIS, NOAA. Earthquake activities in the North part of Vietnam's territory in the past century (1000 ÷ 2008) takes place in separately zones, and they differ between the adjacent zones. They differ in terms of depth, thickness of seismogenic layer and earthquake activity period, therefore can divided the research division into six earthquake zones;

The Viet Bac seismogenics zone: According to statistics there ware 5 earthquakes with magnitude Ms ≥ 5.0 (Richter scale), with the hypocenter occurred in the depth about 7-19km, the layer thickness criteria focus earthquake shock here is around 12km. According to available data, there is a manifest increase in the number of small earthquakes within this zone as result of increasing the quality of the record and observation stations networks also.

Dong Trieu - Cam Pha seismogenics zone: Within this zone there ware 4 events with magnitude Ms ≥ 5.0 (Richter scale) which included the history Feb., 1355 with Ms = 5.5 and three event recorded during the 20^{th} Century and the most destructive event was Bac Giang 06/12/1961 with Ms = 5.9. Almost the earthquakes hypocenter occurred at the depth 9 - 21 km except the Bac Giang event was at 28km in depth. The concentration layer thickness Earthquake shocks in the target zone is around 12 km.

Red River seismogenic zone: Within this zone there ware 8 event with magnitude Ms ≥ 5.0 (Richter scale).The recorded earthquakes with Ms 5 is almost appear in range 5km to 15km of the upper class through Granite layer, other earthquake larger than 5.0 is mainly at a depth of 15-20km at the end of Granite to Basal layer.

Song Da - Song Ma seismogenic zone: There ware 2 most destructive earthquakes in this zone; Yen Dinh - Nho Quan earthquake in 01/06/1635 with Ms = 6.7 and Tuan Giao earthquake on 24/06/1983 with Ms = 6.7. This is most dangerous seismogenic zone in North Vietnam with 11 events of Ms ≥ 5 and densely contribution of small earthquake. The mean depth in this zone is vary from 3 to 20km, the strong earthquake with Ms ≥ 5.0 concentrated within the range 10 to 20km, while smaller events of 4.9 distributed clutter from a few kilometers.

Muong Te - Dien Bien Seismogenic zone: The destructive earthquake occurred in the zone on 1/1/1935 in eastern town of Dien Bien with Ms = 6.8 on the Richter scale. By the end of 2000 (Dang Thanh Hai, 2003) the recorded data in this zone consists of 7 earthquake with Ms = 5.0 ÷ 5.7, 25 earthquake with Ms = 4.0 ÷ 4.8 and 49 events with Ms = 3.1 ÷ 3.9. The depth of hypocenters contribution are in range of 2- 25 km thus the seismogenic thickness is 23 km (from 2 ÷ 25 km). The small events with (Ms< 4.9) are normally at a few to 20 km in depth, while the larger events (Ms>5) are at 15 to 25km.

Song Ca-Rao Nay Seismogenic zone: In this zone, the most destructive earthquake was published in history document, the Vinh earthquake on 1821 with Ms = 6.0. The current observation network has observed two earthquakes with Ms = 5.1 and 5.2, more than 15 earthquakes with Ms = 4.0 ÷ 4.9 and also 15 event with Ms = 3.1 ÷ 3.9 [13]. The main shock occurred at depths from 7 ÷ 20km which is located the upper of Granite - Basalt layer.

4.2. Correlation between nodes and earthquakes

Since the nodes have been outlined from the cartographic sources without field investigations, their natural boundaries have not been defined. Here, as in previous investigations [5, 8], we define the node as a circle of 25 km of radius, centered at the point of intersection of the lineaments. Using this formal node definition, each point of lineament intersection is a node but, in reality, two or three closely situated intersections may belong to the same node. For instance, in the Greater Caucasus, MZ defined 101 intersections of lineaments. The field mapping of the node boundaries brought about the identification of 65 nodes, which contain all 101 intersections; i.e. the majority of nodes are formed by more than one intersection [8, 11, 12]. Recently, Gorshkov et al. [10] made an attempt to map the geometry of the nodes in the Alps-

Dinarides junction zone using large-scale cartographic sources. This approach avoids the overlapping of the circles in areas where intersections are located in a short distance to each other. Therefore, the recognizing areas of potential hazard may be reduced in size, but this procedure of node geometry mapping needs further formalization.

In this work, we recognize the nodes prone to earthquakes with $M \geq 5.0$. To select the sample nodes for the learning stage of the recognition, we use the information on the recorded events with $M \geq 5.0$ located in North Vietnam [23, 24]. As it can be seen in *fig. 4*, the epicenters of the earthquakes considered are located near the intersection of lineaments, i.e. at the nodes. The distance between the epicenters and the points of intersection does not exceed 25km. Therefore we can conclude that the recorded earthquakes nucleate at the nodes, thus it is possible to apply pattern recognition for the node classification.

4.3. Recognition of nodes prone to earthquakes with Magnitude ≥ 5.0

Selection of the training sets for CORA-3 algorithm. At the learning stage all the nodes are a priori divided into three sets. To assemble D_0, we have been looking for the nodes situated most closely to the epicenters listed in *table 1*. On the contrary, to form N_0, we sort out the nodes that are most distant from the epicenters in *table 1*.

Table 1. Classification and number of nodes in each class (Do, No, X)

Class	The number of nodes in each classes	Total numbers
D_0	1, 5, 16, 22, 24, 26, 27, 28, 32, 33, 36, 37, 39, 41, 43, 44, 46, 48, 50, 52, 54, 59, 66, 67, 68, 70, 77, 78, 88, 90, 92, 107, 108, 116, 119, 121, 122, 127, 132	39 nodes
N_0	2, 3, 4, 6, 7, 9, 10, 11, 12, 17, 18, 19, 20, 21, 25, 29, 30, 31, 34, 40, 51, 56, 57, 60, 61, 62, 63, 64, 69, 73, 74, 75, 79, 80, 81, 82, 83, 84, 85, 86, 87, 91, 93, 94, 95, 96, 97, 98, 100, 101, 102, 103, 104, 105, 110, 111, 112, 113, 115, 117, 120, 123, 124, 125, 126, 128, 129, 130, 131, 133	70 nodes
X	8, 13, 14, 15, 23, 38, 35, 42, 45, 47, 49, 53, 55, 58, 65, 71, 72, 76, 89, 99, 106, 109, 114, 118, 134	25 nodes

As a result, 39 nodes out of the 134 delineated in North Vietnam have been included in D_0. The subset N_0 contains 70 nodes. The remaining 25 nodes are not included in the training set because they are either not close enough to the relevant epicenters or not sufficiently distant from them. They are assigned to the set **X** that is not employed for the selection of the characteristic traits; the nodes from the set **X** are classified at the recognition stage.

Parameters of the nodes used for recognition and their discretization. A uniform parameterization of the nodes in the form of a common questionnaire is needed to apply the pattern recognition technique. In general, a questionnaire should reflect the characteristics of tectonic and geological environments responsible for the present-day seismic level. All the parameters to be employed should be available with the same accuracy for the entire study region.

Here, we use the parameters listed in *table 2*. Apart from parameters related to magnetic anomalies, all of them have been employed for the recognition of earthquake-prone areas in previous investigations. Among the many other parameters, that have been tested, the parameters listed in *table 2* have been found sufficiently informative to identify the seismogenic nodes (see the review of this problem by Gorshkov et al. 2003) [8].

The parameters describing the topographic altitudes and the area of soft sediments (*table 2*) characterize indirectly the contrast and intensity of the present-day tectonic movements, while those describing the density of lineaments and gravity and magnetic anomalies can be related to the degree of crust fragmentation and heterogeneity. The values of the parameters have been measured within each node, i.e. inside a circle with 25 km of radius, from available topographic, geological, gravity and magnetic maps as well as from the compiled MZ map (*fig. 4*).

Since the CORA-3 algorithm operates in a binary vector space, the measured values of the parameters are transformed into binary vector space by discretization and coding. The range of the value of each parameter is divided into two or three parts (interval open to the left) by specifying one or two thresholds of discretization. This leads to the loss of some information but it makes the results of the recognition more stable to the fluctuations in the data. One-threshold discretization considers two intervals of the real values, which are converted into one binary component with the value 1 (“small”) or 0 (“large”). Correspondingly, in two-threshold discretization the real values of the parameters are converted into two binary components with the values 11 (“small”), 01 (“medium”) or 00 (“large”). The discretization has been done with the a priori division of the nodes into subsets D_0 and N_0. The thresholds of discretization are listed in *table 2*.

Table 2. Parameters used for pattern recognition and thresholds of their discretization

Parameters	Thresholds of discretization
A)Topographic parameters	
Maximum topographic altitude, *m* (Hmax)	1397 1784
Minimum topographic altitude, *m* (Hmin)	195
Relief energy, *m* (ΔH) (Hmax - Hmin)	1212
Distance between the points Hmax and Hmin, *km* (L)	9.8 15
Slope, (ΔH/L)	97.85
B) Geological parameters	
The portion of the node area covered by soft (quaternary) sediments, %, (Q)	0.45
C) Parameters from the morphostructural map	
The highest rank of lineament in a node, (HR)	2
Number of lineaments forming a node, (NL)	2
Distance to the nearest 1st rank lineament, *km,* (D1)	52.2 124.8
Distance to the nearest 2nd rank lineament, *km,* (D2)	32 62
Distance to the nearest node, *km,* (Dn)	23.1
D) Morphological parameter (Mor)	
This parameter is equal to one of the following six values in accord with the morphology within each node:	
(1) mountain and plain (m/p)	
(2) mountain and piedmont (m/pd)	
(3) mountain and mountain (m/m)	
(4) piedmont and plain (pd/p)	
(5) piedmont only (pd)	
(6)- plain only (p)	
E) Gravity parameters	
Maximum value of Bouguer anomaly, *mGal*, (Bmax)	-92 -56
Minimum value of Bouguer anomaly, *mGal,* (Bmin)	-114 -82
Difference between Bmax and Bmin, *mGal* ,(ΔB)	16 27
F) Magnetic parameters	
Maximum value of magnetic anomaly, *nT*, (Mmax)	10
Minimum value of magnetic anomaly, *nT,* (Mmin)	-130
Difference between Mmax and Mmin, *nT* ,(ΔM)	60 130

Result of recognition of nodes prone to earthquakes with M ≥ 5.0. The nodes have been classified by CORA-3. With $k_1 = 6$, $\bar{k}_1 = 2$, $k_2 = 16$, and $\bar{k}_2 = 1$, the algorithm selected nine D traits and twelve N traits (*table 3*), controlling the classification given in *table 3*, when $\Delta = 0$. The classification reported in Table is the most stable among the other ones defined by different of $k_1, \bar{k}_1, k_2, \bar{k}_2$. Of 134 nodes, 92 (68%) are classified D and 42 (32%) N. D is formed by 36 objects originally in D_0, 37 originally in N_0, and 19 belonging to the set X. D nodes are shown by circles in *fig. 5*. The nine parameters that compose the decision rule (*table 3*) are essential for the recognition. All earthquakes with $M \geq 5.0$ recorded in North Vietnam (*fig. 4*) belong to D nodes.

Table 3. Characteristic traits of D and N nodes in North Vietnam

No	Parameters								
	Hmaxm	LKm	dH/L	HR	D 1km	D 2km	BmaxmGal	BminmGal	Mor
					D-traits				
1	≤1397						≤-92	>-114	
2			>97.85		>124.8	≤62			
3			≤97.85		≤124.8	≤32			
4			≤97.85	1^{st} or 2nd	≤124.8				
5		>15	≤97.85		≤52.2				
					N-traits				
1							>-92	>-114	m/p *or* m/pd
2					≤124.8		>-92		m/p *or* m/pd
3					>52.2		>-92		m/p *or* m/pd
4				3rd			>-92		m/p *or* m/pd
5		>9.8					>-92		m/p *or* m/pd
6					≤124.8	≤62			m/p *or* m/pd
7			>97.85		≤124.8				m/p *or* m/pd
8			≤97.85		>52.2		>-92		

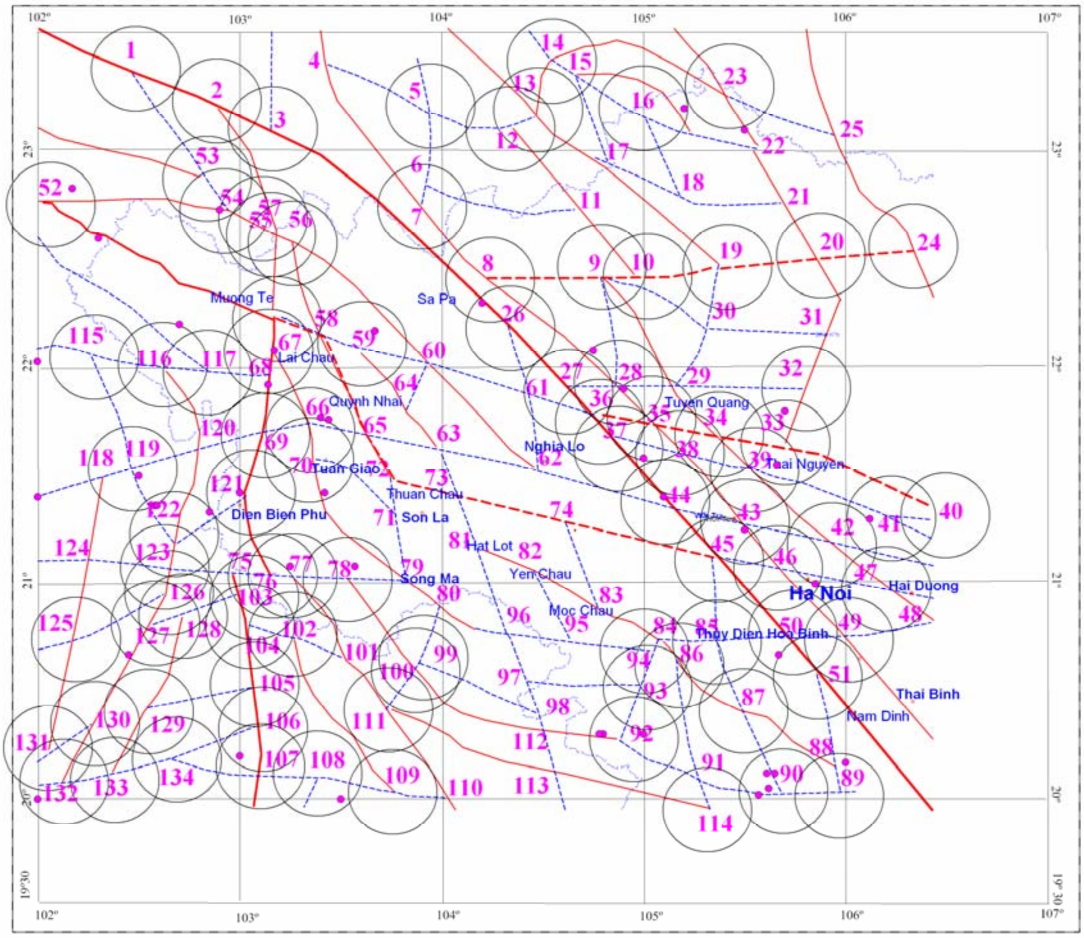

Fig. 5. Earthquake-prone areas of *M*≥ 5.0 recognized in North Vietnam; Circles show D nodes prone to *M*≥ 5.0 events; Non-circled intersections of the lineaments are N nodes. (Lines and dots are the same as in Fig. 4.)

5. Discussion and conclusions

In this section, we focus on the analysis of the recognition of the nodes prone to M ≥ 5.0 events including the spatial distribution of D nodes and the interpretation of their characteristic traits.

All earthquakes with M≥ 5.0 reported by catalogs are related with recognized D nodes (*fig. 4*). D nodes, where earthquakes M ≥ 5 are not recorded up to date, have been recognized over the entire region. D nodes where events M ≥ 5 does not yet occur have been identified over the study region.

At the learning stage the algorithm CORA-3 selected five D-traits and eight N-trait (*table 3*) that discriminate seismogenic nodes (D) from nonseismogenic ones (N) with respect to target magnitude M ≥ 5.0. The traits include nine parameters out of 18 ones that were used for description of the nodes (*table 2*).

The magnetic anomalies that were tested in the study region turned out to be not informative for the discrimination D and N nodes.

Table 2 shows that D nodes differ from N nodes mainly in morphology, gravity anomalies and highest rank of lineament at the node. High values of the Bouguer anomaly (Bmax ≤ -92 mGal) are characteristic to D nodes, while N nodes are characterized by smaller values of the anomalies (Bmax > -92 mGal). Trait №4 in *table 3* indicates that some of D nodes include lineaments of the 1st or 2nd rank. That means that some of D nodes are located on the boundaries of the larger blocks (see *fig.4*). This study demonstrates that the pattern recognition approach to identify earthquake prone areas is applicable to a region, like North Vietnam, that is characterized by a complex and heterogeneous tectonic structure and topography. The recognition performed, pinpoints a number of D nodes where moderate events have not been recorded up to now. This generates the need for interdisciplinary efforts and attempts to explain how the structure and the dynamics of the lithosphere in the region brings into existence the seismogenic nodes at the sites represented in this work.

The paper completed under support from Institute of Geophysics, VAST of Vietnam and partly grants contribution from ICTP, UNESCO as Junior Associate visitor in framework of 2010. A review paper of this result is influenced by many ideas heard from Dr. Thang N.G, colleagues of IGP and kindly help from Prof. Abdelkrim Aoudia, ESP section of ICTP.

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