

**Paper 1**

**Characteristics of dense nests of deep and  
intermediate-depth seismicity**

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# 1. Characteristics of dense nests of deep and intermediate-depth seismicity

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## 1.1. Abstract

The aim of this paper is to review the intermediate or deep nests of earthquakes, which are not related to volcanoes. A nest is defined by stationary activity and not by earthquake swarms which take place occasionally, although each nest may include several swarms. A nest should be active in a more or less continuous mode with the events concentrated in a small volume so the activity in this volume is substantially larger than in the surrounding areas. The three well known intermediate depth nests in the world are the Bucaramanga nest in Colombia at  $6.8^{\circ}\text{N}$  and  $73.1^{\circ}\text{W}$  and centered at 160 km depth, Vrancea in Romania at  $45.7^{\circ}\text{N}$  and  $26.5^{\circ}\text{E}$  at depths between 70 and 180 km, and the Hindu Kush in Afghanistan. In Hindu Kush the earthquakes tend to occur as clusters of events but the majority are located at  $36.5^{\circ}\text{N}$  and  $71^{\circ}\text{E}$  in depth between 170-280 km. Here we have tried to compare the size, tectonic setting and focal mechanisms of their earthquakes to understand what mechanisms are responsible for existence of nests. All these nests are located in old subducted slabs. Among them, the smallest and the most active nest is the Bucaramanga, and the deepest nest is Hindu Kush. The focal mechanism of earthquakes in Hindu Kush and Vrancea show reverse faulting, while in Bucaramanga the focal mechanisms are variable but the majority of them have reverse mechanisms. Almost all studies agree that the seismicity in Vrancea is the result of progress of slab detachment from its upper part (slab break-off). In Bucaramanga and

Hindu Kush, the responsible deriving force is not known exactly. Many studies suggest that in Bucaramanga, the driving mechanism is fluid migration or dehydration reactions or a complex concentrated stress field, while in Hindu Kush the possible driving mechanism is distorted slab or collision of two subducting slab from opposite directions. We also investigated some reported possible nests in the world using ISC data. We found evidence that there are probably nests in Fiji, in Chile-Argentina border region and in Ecuador.

## 1.2. Introduction

In a few places around the world, unusual concentrated seismic activity has been observed. This kind of activity has been labelled as seismic nest. A nest is defined by high stationary activity relative to the surroundings. A nest should be active in a more or less continuous mode at a rate higher than the adjacent area and with the hypocenters concentrated in a small volume. Earthquake swarms are not defined as nests although a nest may include several swarms. Within this definition, two classes of nests can be defined: A) Intermediate and deep nests related to subduction zones processes and B) shallow or intermediate depth nests related to volcanic activity in overriding slabs. For type B nests, there are numerous reports in different parts of the world. For example, some nests in Japan (Kanto district) have been suggested as shallow nests, with high rate of energy release (Usami & Watanabe, 1980). Similar activity has been seen in the vicinity of other volcanoes in Central America (Carr & Stoiber, 1973), in New Zealand (Blot, 1981*a*), in New Hebrides (Blot, 1981*b*) and in the Aleutians (Engdahl, 1977), which are intermediate depth nests ( $70 < \text{depth} < 160 \text{ km}$ ). More than 40 such nests are identified in the circum Pacific and Indonesian arcs. These nests may be related to melting near the upper surface of the under-thrusted slab. A fluid phase, either silicate melts or a hydrous fluid released by dehydration of the slab, would lower the strength of the slab and create an aseismic zone beneath the active volcanoes. Nests of earthquakes can then develop

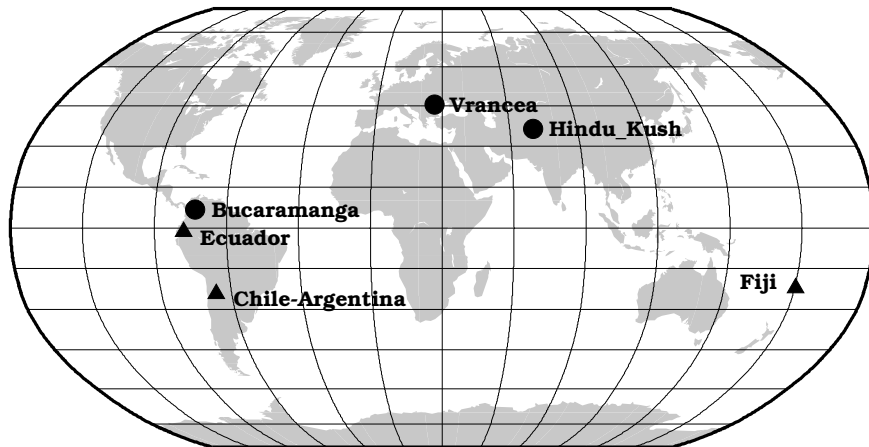


Figure 1: Location of known (circles) and possible (triangles) nests investigated in this research. Bucaramanga nest located in Colombia, Vrancea in Romania and Hindu Kush in Afghanistan.

by stress concentration at the margins of the weak zones (Carr, 1983).

Nests of type A are few and far apart. There are only 3 well recognized nests of this kind: the Bucaramanga in Colombia, the Vrancea in Romania and the Hindu Kush in Afghanistan (Tryggvason & Lawson, 1970; Schneider *et al.*, 1987; Dewey, 1972; Frohlich *et al.*, 1995). A few more have been suggested in Chile-Argentina, Ecuador, Fiji (Schneider *et al.*, 1987), Italy and Burma (Tryggvason & Lawson, 1970).

In this paper, information on seismicity, tectonics, focal mechanisms and the possible origin of the nests in Bucaramanga, Vrancea and Hindu Kush are reviewed and compared in order to find common characteristics.

Possible additional nests are then evaluated using these criteria to determine if they can be labelled nests. For this evaluation, we will use ISC data for both the known nests and the possible nests. It is possible that poor coverage of seismic stations in some areas will make the identification of possible nests doubtful, however, by initially using global data for both the known and possible nests, a similar data base is used for all comparison. We have divided this review to two parts: I (known nests) and II (possible nests). Figure 1 shows the location of known and possible nests that will be discussed in this paper. The global seismicity data have been selected from the ISC database using the time period

1964 to the end of November 2000.

### **1.3. Part I. Known nests**

This part concentrates on the three known nests (Bucaramanga, Vrancea and Hindu Kush) to help us to understand the behaviour, mechanism and possible origin of these nests.

#### **1.3.1. General view**

The Bucaramanga nest, which is located in the north east of Colombia, is an intermediate depth nest centered around 160 km depth at about 6.8°N, 73.1°W. (Tryggvason & Lawson, 1970; Schneider *et al.*, 1987; Dewey, 1972; Frohlich *et al.*, 1995; Ojeda & Havskov, 2001). There are many studies about this nest with both local and teleseismic data, which all show that the Bucaramanga nest has a small volume. For instance Tryggvason & Lawson (1970) and Dewey (1972) claimed that the Bucaramanga seismic nest is less than 10 km in radius. Schneider *et al.* (1987) found that the nest has a volume of about 8 km (NW) by 4 km (NE) by 4 km (depth) centered at 161 km depth. Pennington *et al.* (1979) suggested that the nest has a source volume with a diameter of 4-5 km. All of these values are based on local data. Using teleseismic data, Frohlich *et al.* (1995) found a volume of about  $11 \times 21 \times 13 \text{ km}^3$ , showing that teleseismic data has a poorer resolution than local data.

The Vrancea region in Romania is in a complex tectonic zone, which is characterized by clustered intermediate depth seismic activity (Oncescu, 1987). The Vrancea nest is located at 45.7°N and 26.5°E. The dimension of the Vrancea nest, based on local data, has been considered to be  $20 \times 50 \text{ km}^2$  laterally and 110 km vertically (between 70-180 km) (Sperner *et al.*, 2001).

The Hindu Kush area in Afghanistan is one of the most intriguing seismic zones of the

world, because a large number of earthquakes occur in a limited zone (Nowroozi, 1971). The majority of these events are centered at  $36.5^{\circ}\text{N}$ ,  $71^{\circ}\text{E}$ , within 175-250 km depth and, in an east-west alignment with a length about 120 km and a width around 30 km.

### 1.3.2. Seismicity of the known nests

For each nest, different studies have reported the rate of seismicity, as compared to the surrounding area, and the 3D size of the nests using both global and local data. From the previous section, it is clear that volumes of nests are different and using uneven data sources might cause part of these differences. In order to get a more quantitative comparison, we will use ISC data to compare the nests. Figures 2, 3 and 4 show the map and 3D view of the nests based on the ISC database.

The nests are clearly seen as high activity areas compared to the seismicity in the surrounding areas. The size of the three nests, Bucaramanga, Vrancea and Hindu Kush, based on ISC data, are  $33 \times 35 \times 35$ ,  $25 \times 55 \times 110$  and  $60 \times 80 \times 100 \text{ km}^3$  respectively, which is substantially larger than  $8 \times 4 \times 4$  (Schneider *et al.*, 1987),  $20 \times 50 \times 110$  (Sperner *et al.*, 2001) and  $120 \times 30 \times 75 \text{ km}^3$  (Nowroozi, 1971) as have been observed from the local studies. The size of the nests are also quite different and this is seen from both local and global data.

The geometry of the Bucamaranga nest based on both ISC (Figure 2b) and local data (Schneider *et al.*, 1987; Dewey, 1972; Frohlich *et al.*, 1995; Ojeda & Havskov, 2001) shows that it is a very dense clustering of earthquakes within the subducted slab. In Vrancea, the ISC database shows a nearly vertical slab (Figures 3b), which is in agreement with observed geometry from local data (Sperner *et al.*, 2001). In Hindu Kush, based on local data, there is an East-West alignment of deep earthquakes. Its length is about 120 km and its width is about 25 to 30 km. The majority of events are within 175-250 km depth. There is another alignment with a  $\text{N}45^{\circ}\text{W}$  trend. This alignment has a length perhaps more than 200 km and a width nearly 100 km, the earthquakes are within

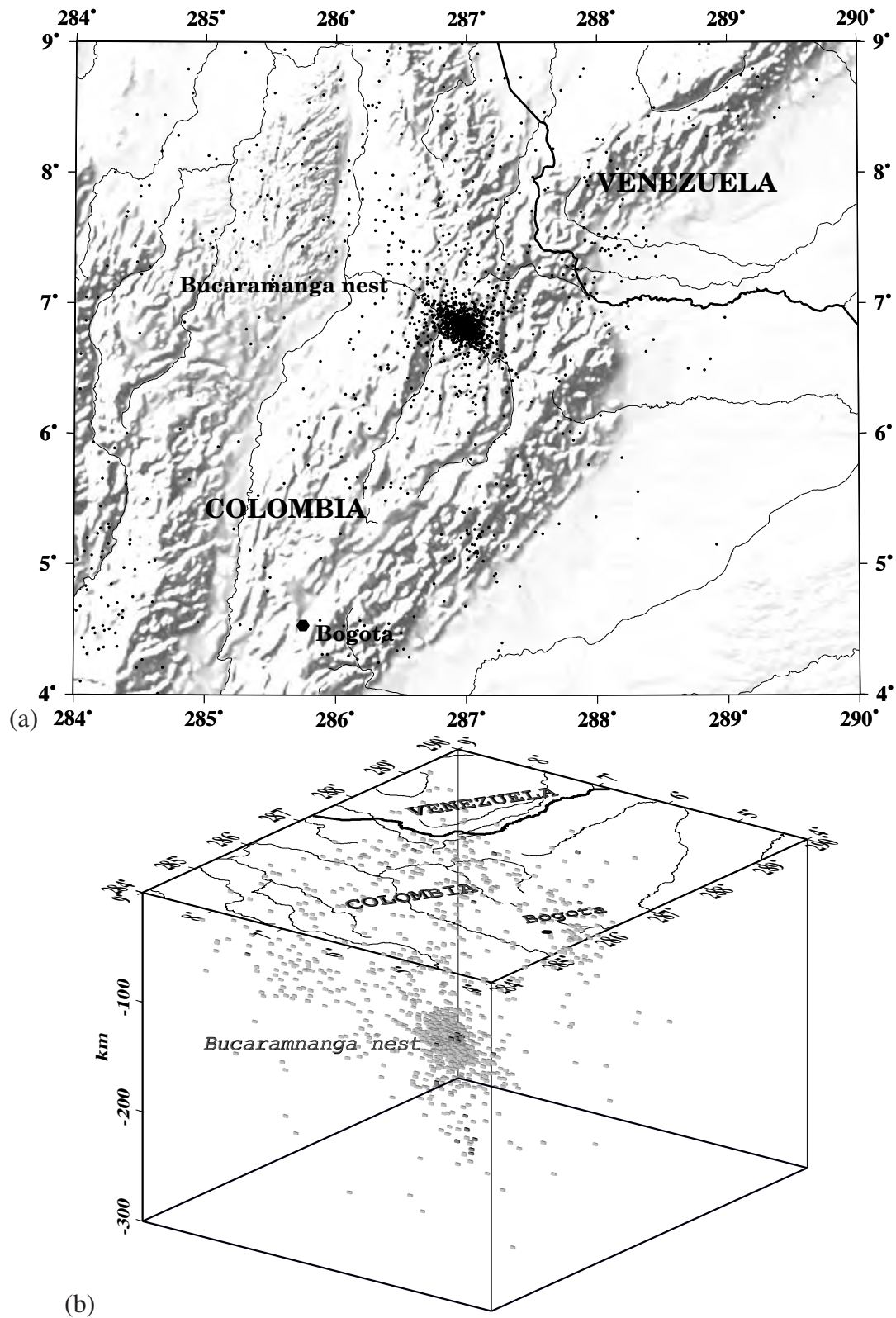


Figure 2: (a)Map and (b)3D view of the Bucaramanga nest in Colombia. Seismicity has been collected from ISC catalog (1964-2000).



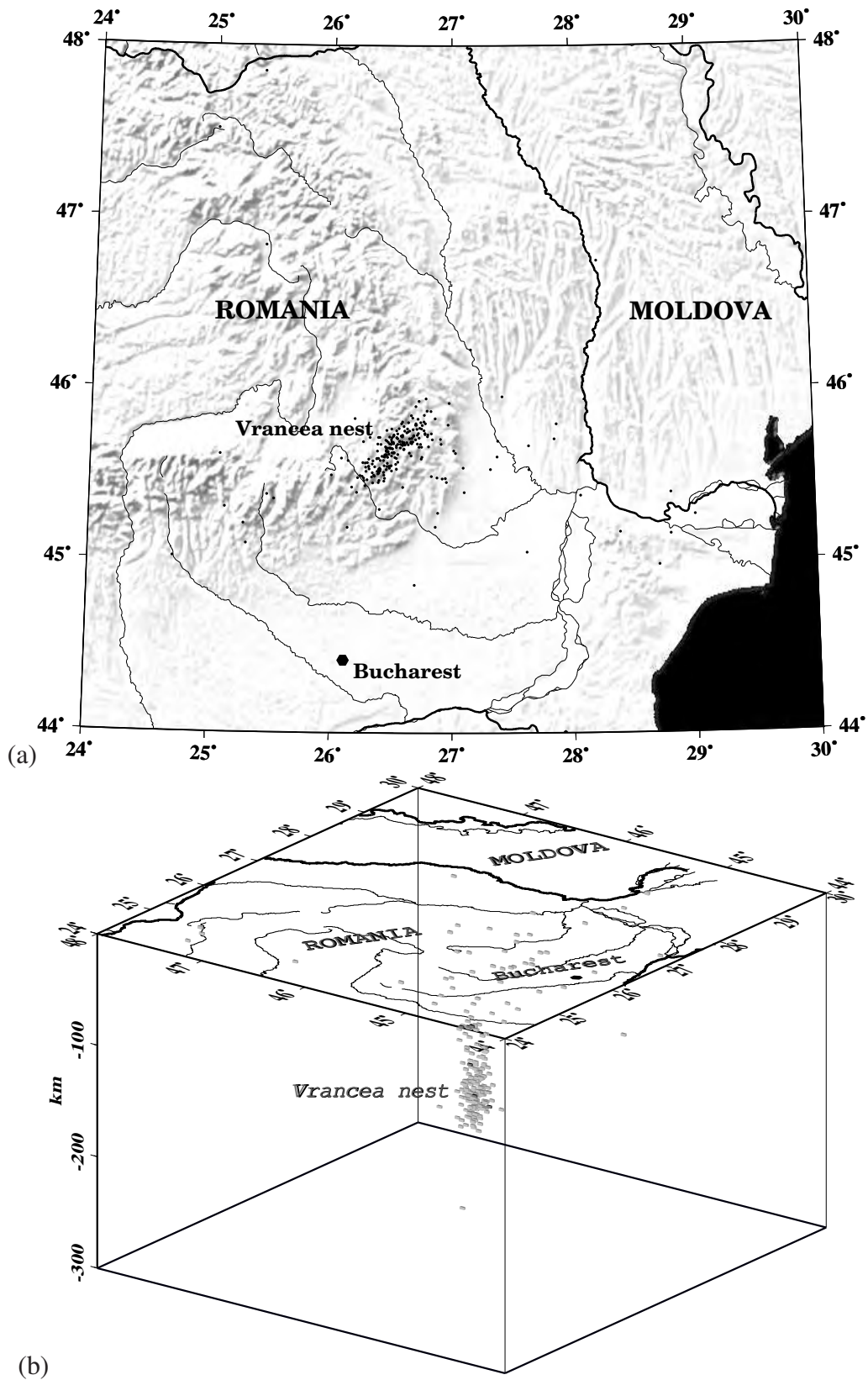


Figure 3: (a)Map and (b)3D view of the Vrancea nest in Romania. Seismicity has been collected from ISC catalog (1964-2000).

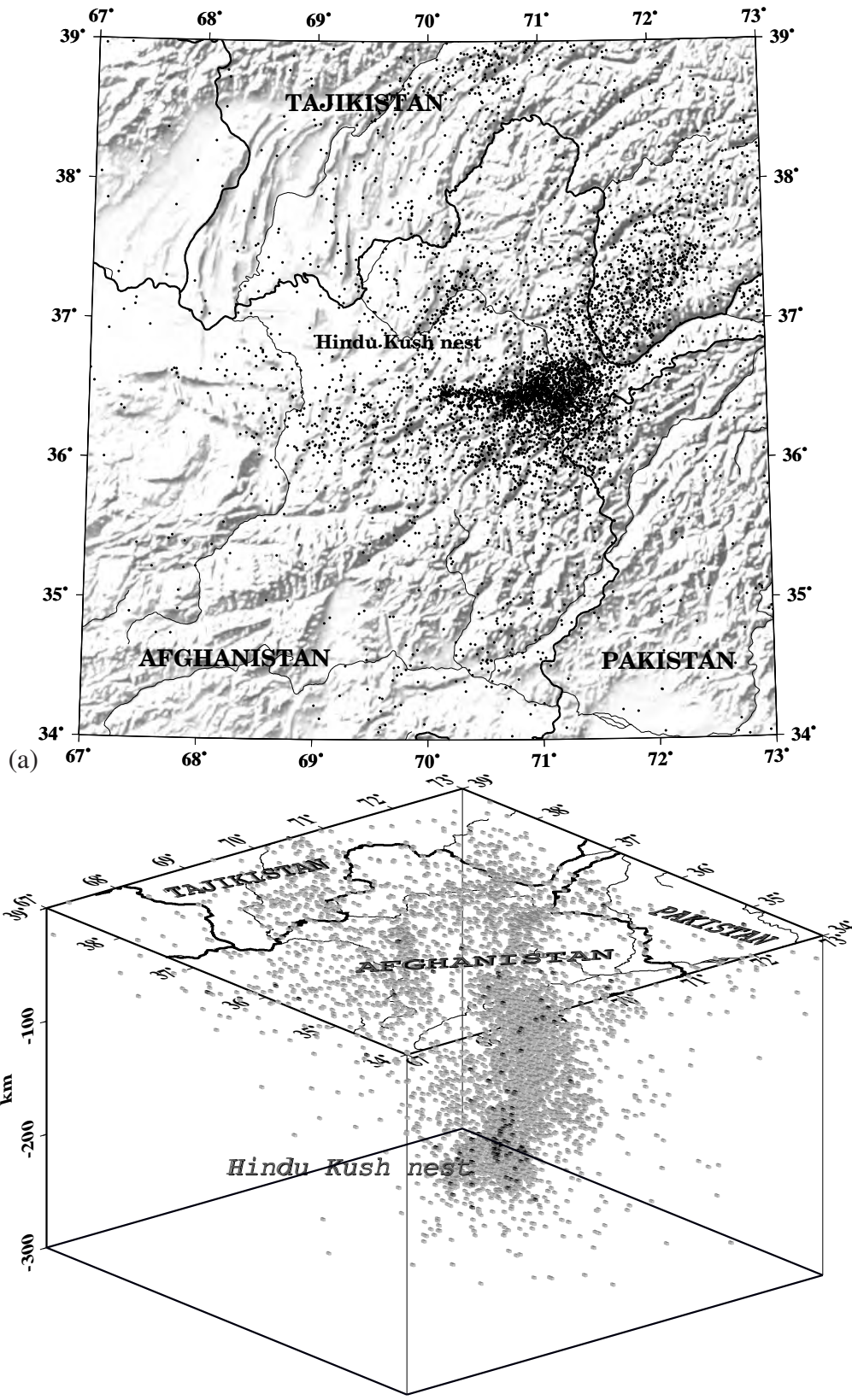


Figure 4: (a) Map and (b) 3D view of Hindu Kush nest in Afghanistan. Seismicity has been collected from ISC catalog (1964-2000).

approximately the upper 150 km. A zone of less intensive activity connects these two zones (Figure 4a). The majority of earthquakes in this region are within a nearly vertical, contorted slab like feature, which is concentrated in an East-West alignment at about  $36.5^{\circ}\text{N}$  and  $71^{\circ}\text{E}$  (Nowroozi, 1971). The ISC data (Figure 4b) shows complete agreement with local observation (Nowroozi, 1971). Base on ISC data, there is also another nest just above the major nest in the depth interval between 81-141 km and its volume is about  $50 \times 40 \times 60 \text{ km}^3$ . This nest is separated from the nest below by a zone with less seismic activity. In general, in Hindu Kush, the events tend to occur as separated clusters that leave aseismic gaps between the clusters (Chatelain *et al.*, 1980).

The contrast in seismicity between the nests and the surrounded area is clearly seen for all nest (Figures 2, 3 and 4). In order to compare the rate of seismicity for the three nests, the detection threshold for each was determined by plotting the Gutenberg-Richter relation (using  $M_b$ ) for each area. The threshold for Hindu Kush, Bucaramanga and Vrancea were 4.1, 4.4 and 4.8 respectively and a common detection threshold of 4.8 was therefore selected. Based on ISC data, the Hindu Kush nest has the highest activity with 7096 events compared to 2708 events in Bucaramanga and 249 events in Vrancea, but it also has the largest volume. 956 events in Hindu Kush, 462 events in Bucaramanga and 57 events in Vrancea had a magnitude larger than 4.8 ( $M_b$ ). If we normalize the size of the nests to the size of the Hindu Kush nest ( $48\text{E}+4 \text{ km}^3$ ) and find the number of events with  $M_b > 4.8$  per normalized volume, we see that the Bucaramanga nest is the most active nest, with 5500 events per normalized volume compared to 956 events per normalized volume in Hindu Kush and 178 events per normalized volume in Vrancea. This normalization is of course approximate due to the uncertainties in the size and will have a larger effect on the smallest nest, however, there is no doubt that Bucamaranga is the most active in terms of rate of seismicity per volume. The b-value in Bucaramanga is 1.17, in Vrancea it is 1.0 and in Hindu Kush it is 1.43, which all are close to 'normal' indicating that this is normal tectonic activity and cannot be considered swarm activity

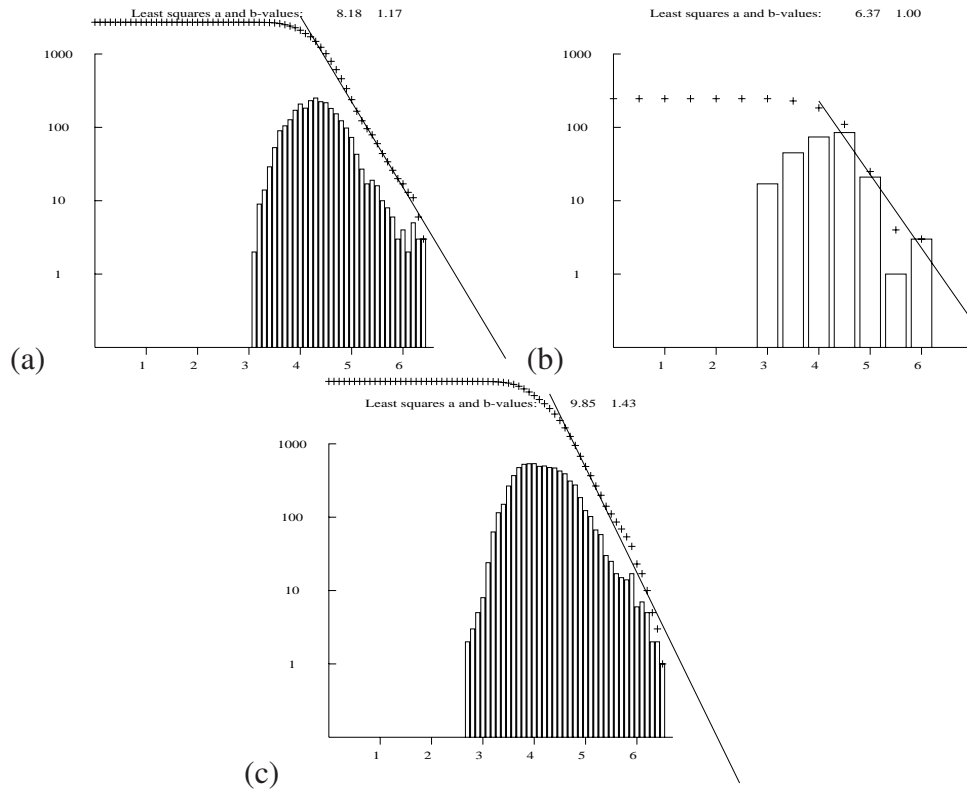


Figure 5: The Gutenberg- Richter diagram for (a)Bucaramanga, (b)Vrancea and (c)Hindu Kush nests.

(Figure 5).

For each nest, we have looked at the size of the largest events. This is important since a question that naturally arises is whether a cause for the large number of medium sized events is the lack of large events. Since b-values are close to normal, there is no indication of this from the distribution of events in the ISC catalog. Table 1 shows the summary of seismicity information about the known nests. It shows that the largest reported earthquakes for these nests have more or less the same magnitude, 6.4 ( $M_b$ ) in Bucaramanga and Vrancea and 6.5 ( $M_b$ ) in Hindu Kush. In the area surrounding (about 70 km away in every direction) the Bucaramanga nest the maximum magnitude in  $M_b$  is 5.7, in Hindu Kush is 6.0 and in Vrancea it is 5.0 (Table 1).

Table 1: Summary of the observed Seismicity in the known nests.

Nests	Bucaramanga	Vrancea	Hindu Kush
Location	6.8°N,73.1°W	45.7°N,26.5°E	36.5°N,71°E
Depth (km)	150-170	70-180	170-280
Size(ISC)	33×35×35	25×55×110	60×80×100
Size(local)	8×4×4	20×50×110	55×30×120
Normalized volume (ISC)( $V_N$ )	0.084	0.32	1
Total number of events	2708	249	7096
Events $M_b > 4.8$	462	57	956
Number of events with $M_b > 4.8$ per ( $V_N$ )	5500	178	956
Average number of events with $M_b > 4.8$ per / month	1.1	0.13	2.2
b value	1.17	1.0	1.43
Largest reported event $M_b$ in nest	6.4	6.4	6.5
Largest reported event $M_b$ in surrounding area	5.7	5.0	6.0
Seismic moment release rate inside the nest (Nm/Y)	1.27E+23	1.48E+24	4.13E+24
Seismic moment release rate around the nest (Nm/Y)	2.44E+22	1.66E+21	6.82E+22

### 1.3.3. Tectonic Setting

Understanding the tectonic setting in the nests area and comparing them should give us a better idea about the processes that may be responsible for such a seismic activity. The following section will therefore look into the detailed tectonics of each nest and its surrounding.

The tectonic of Colombia is very complex. Many authors have discussed it but no clear conclusions have been reached (Taboada *et al.*, 2000; Kellogg & Vega, 1995; Malave & Suarez, 1995; Van der Hilst & Mann, 1994). Based on one of the latest tectonic models for Colombia made using local seismology, tectonics and global tomography, (Taboada *et al.*, 2000), there are four plates (Figure 6) which converge: The North Andes block as part of the South American plate, the Panama block, the Caribbean and the Nazca plates. The North Andes block is bound by the Colombia-Ecuador trench and Panama on the west, the South Caribbean deformed belts to the north and the Frontal fault system to the east (Pennington, 1981; Adamek *et al.*, 1988; Kellogg & Vega, 1995). It is moving northeast relative to a stable South America and compressed in the EW direction, whereas in the north, it is converging with the Caribbean plate. The south Caribbean deformed belt is the major boundary between the Caribbean and South American plates (Van der Hilst & Mann, 1994; Kellogg & Vega, 1995). Pennington (1981), by using seismicity and earthquake focal mechanisms, defined two distinct segments of the subducted lithosphere inside Colombia. First the Bucaramanga segment, from 5.2°N to 11°N, was suggested to be a single Benioff zone formed by subducted lithosphere of the Caribbean sea floor northwest of Colombia with a dip at 20°-25° toward N109°E. In the northern part of the North Andes block, significant displacement has occurred on the Santa Marta-Bucaramanga fault, which is a left lateral fault trending northwest - southeast (Figure 6). The Frontal fault system consists of sub parallel westward dipping faults. Pennington (1981), based on a study of focal mechanisms, proposed that the North Andes block is separated from the rest of South America along the Frontal fault system. Second, the

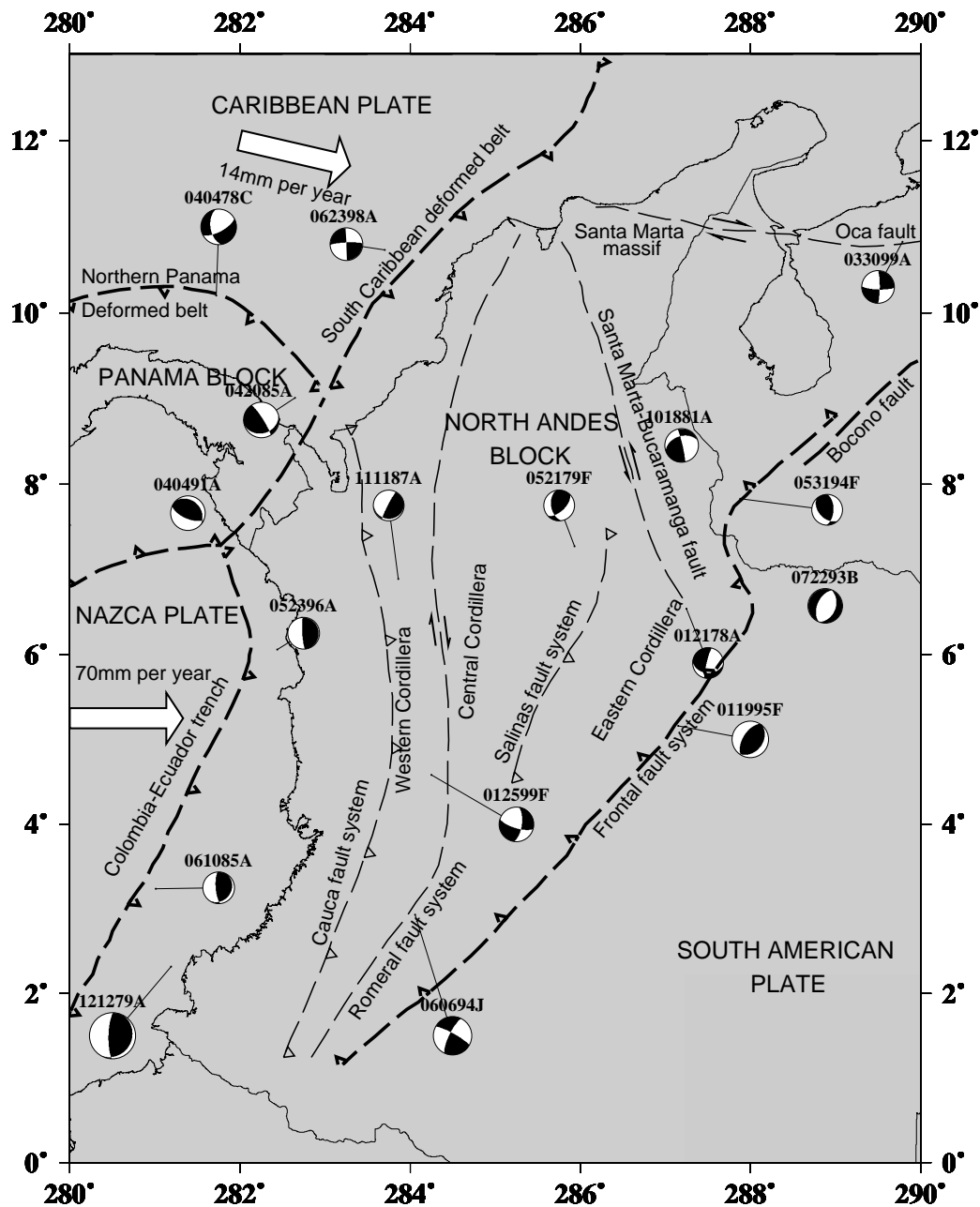


Figure 6: Major tectonic setting in Colombia. Dashed lines show the surface trends of faults and plate boundaries Taboada *et al.* (2000). The arrows show the direction of movement between Nazca, Caribbean and south American plates as presented by Freymueller *et al.* (1993) (From Ojeda & Havskov (2001)).

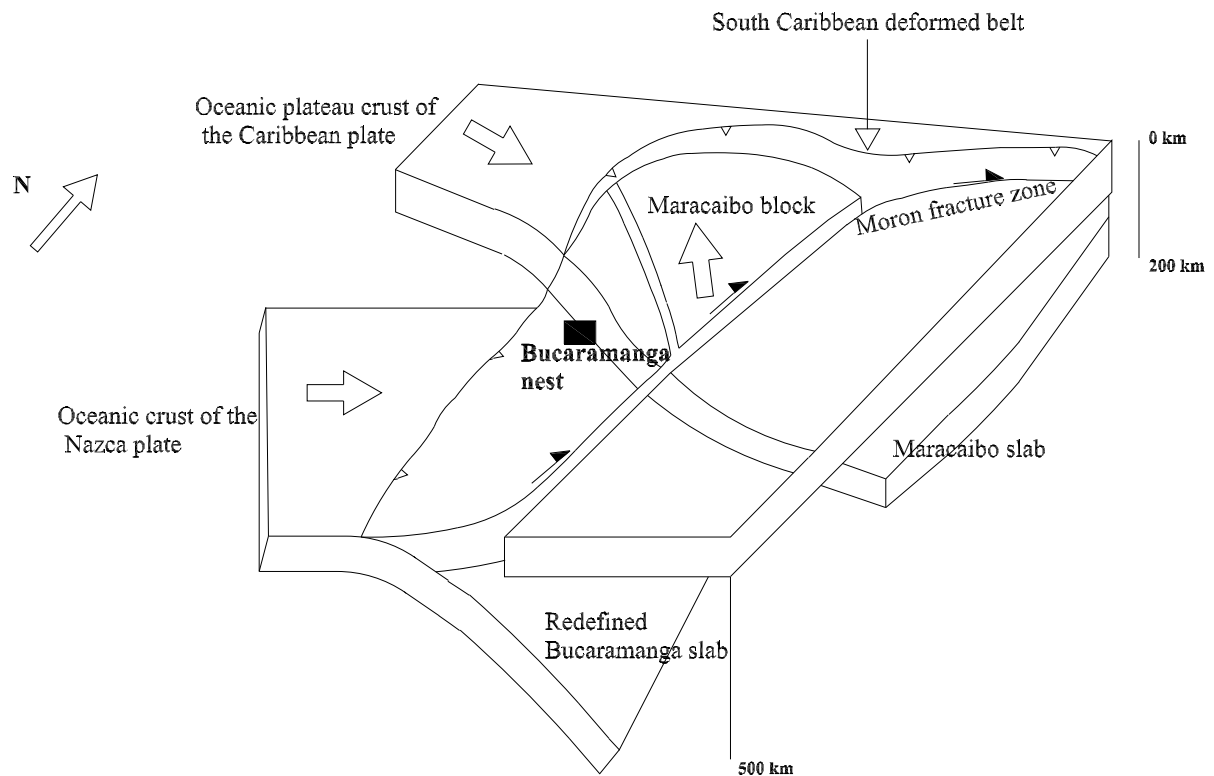


Figure 7: Schematic block diagram summarizing geometry and extent of subducted slabs inferred from Pennington (1981), Using traditional seismology and tomographic inversion. (after Van der Hilst & Mann (1994)).

Cauca segment, south of  $5.2^{\circ}\text{N}$ , was suggested to be a part of the Nazca plate under thrusting South America. In spite of the differences among models for the location of the Caribbean-south American plate boundary and the direction of convergence of the two plates (Minster & Jordan, 1978; Kafka & Weidner, 1981; Kellogg & Bonini, 1982; Sykes *et al.*, 1982), these models are for the most part consistent with the suggestion that the Bucaramanga nest is within a zone or segment of a subducted oceanic lithosphere originally derived from the Caribbean plate (Ojeda & Havskov, 2001). The dip of Wadati-Benioff zone is less than  $30^{\circ}$  from the trench to the nest and increase to near vertical in the vicinity of the nest (Schneider *et al.*, 1987). On the other hand, there is a suggestion that there are two slabs in western Colombia and Venezuela, the Maracaibo and the redefined Bucaramanga slab (Van der Hilst & Mann, 1994) (Figure 7).

The Maracaibo slab, coinciding with most of Bucaramanga slab previously defined by



Pennington, dips in a direction of  $150^\circ$  at an angle of  $17^\circ$  to a depth of 275 km and correlates with the subducted late Cretaceous oceanic plateau of the Caribbean plate. Further south, a second slab dips at an angle of  $50^\circ$  in a direction of  $125^\circ$  to a depth of at least 500 km and correlates with the subducted oceanic crust of the Nazca plate and the down dip extension of the Panama island arc (redefined Bucaramanga slab). This area is characterized by the absence of an active volcanic arc, an anomalously wide topographically uplifted and tectonically active area, and the northward extrusion of the Maracaibo block along the active strike slip faults and it seems that the Bucaramanga nest is located within the redefined Bucaramanga slab, just south of overlap (Figure 7)(Van der Hilst & Mann, 1994).

The Vrancea seismic region is also a complex tectonic zone, where the driving mechanism of intermediate depth events has been understood as a collision between three tectonic units of the Eastern-European platform, the Moesian sub-plate and Inter-Alpine sub-plate (Onicescu, 1987). Bleahu *et al.* (1973) and Onicescu (1984) suggested that there is a NE-SW oriented paleo-subduction that is now decoupled from the crust and generating intermediate depth seismic activity at the limit of the separation. Based on relocated hypocenters of events (Onicescu, 1984, 1986), the lateral extent of Vrancea nest would not exceed 20 km.

Based on the Tertiary-Quaternary tectonic evolution of the Carpathians (which includes Vrancea), the nest is located on the SW-to W-dipping subducted slab. During Cretaceous time, this subduction was active along the whole Alpine-Carpathian arc. However after the Eocene continental collision in the Alps, subduction continued in the Carpathians only where an embayment in the European continental margin provided space. Then subduction has retreated (Royden, 1988), which is the main driving mechanism for the Miocene motions of the two intra-Carpathian blocks, North Pannonian and Tisia-Dacia (Figure 8).

These blocks moved independently with different directions and velocities, confined

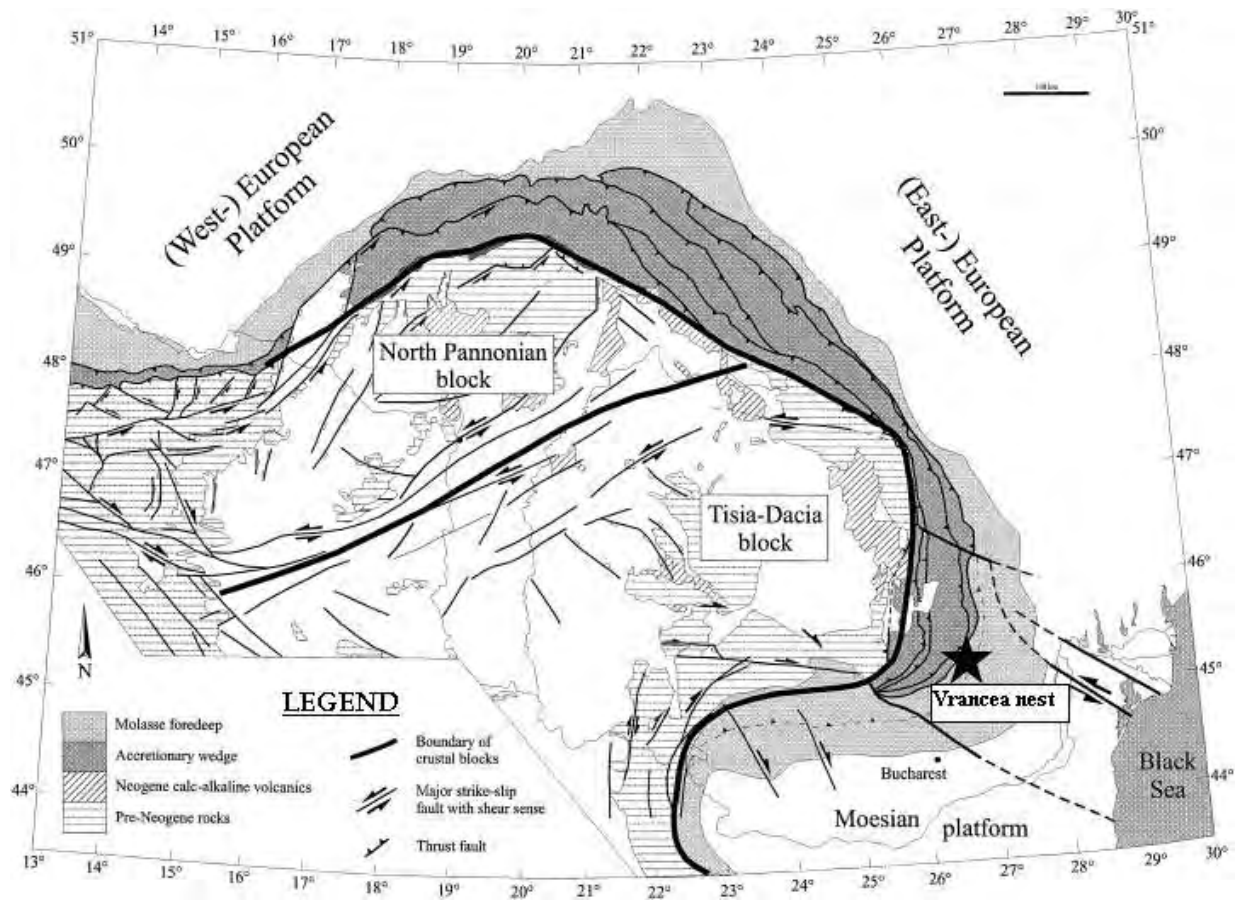


Figure 8: Tectonics of Carpathian-Pannonian region showing Tertiary- Quaternary structures and the location of the intermediate depth earthquakes in SE Carpathians (from Sperner *et al.* (2001)).

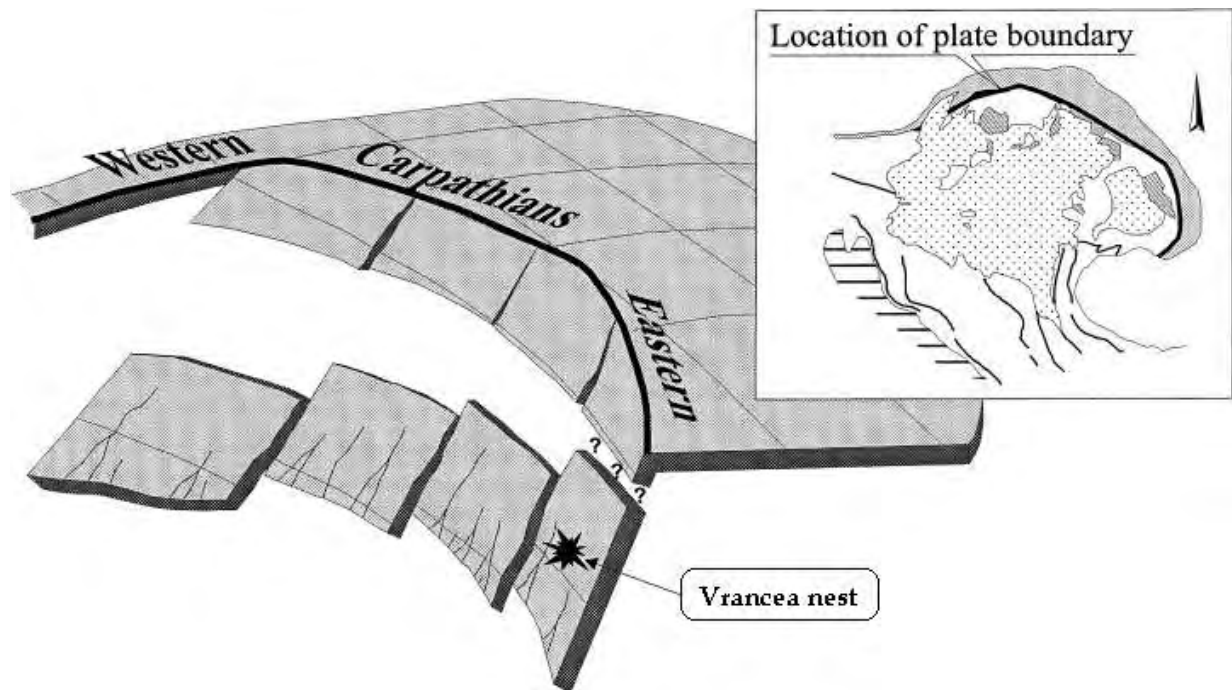


Figure 9: Model for slab break-off beneath the Carpathian arc. The slab segment in the northern parts of already detached (today they are already sunk into the deeper mantle); the south easternmost segment is still mechanically coupled with the European plate (from Sperner *et al.* (2001)).

only by geometry of the continental embayment into which they moved. Rotation of blocks has been highlighted by paleomagnetic data, which reveal a 40° anti clockwise rotation of the northern block (Márton & Fodor, 1995) and 60° clockwise rotation of southern block since early Miocene times (Pâtracscu *et al.*, 1994). Continental collision started in northernmost part of the Carpathians and later shifted towards the SE and S (Jtícek, 1979), leading to corresponding shift of the fore-land basin depocentres (Meulenkaamp *et al.*, 1997) and of volcanic activity (Pécskay *et al.*, 1995). The absence of intermediate depth seismicity in the northern part of the Carpathians indicates that this regional continental collision was followed by slab detachment. Corresponding to collision in the northern Carpathians, detachment also started in the North and propagated towards the south (Figure 9). Thus, today, the last slab fragment hangs beneath the south eastern bend of the Carpathian arc exactly where the Vrancea nest is located (Sperner *et al.*, 2001).

There are different views about Hindu Kush tectonics. Some believe that as India approached Eurasia, the Tethys Ocean subducted beneath Eurasia apparently along the Indus suture zone (Dewey & Bird, 1970; Gansser, 1964, 1966). This suture, east of 76°E, is generally assumed to be composed of only a single belt of ophiolites (Gansser, 1966, 1977). In the framework of plate tectonics theory, deep seismic zones are regarded as zones of stress release during the subduction of oceanic lithosphere, but such an explanation for Hindu Kush is complicated by considering that continental lithosphere includes a thick, low-density crustal layer which may make lithospheric subduction more difficult. Thus, seismicity in regions of continental collision is often regarded as being produced by relics of oceanic lithosphere subducted before the collision (McKenzie, 1969; Isacks & Molnar, 1971; Solomon & Butler, 1974). Another view claims that the configuration of the Hindu Kush seismic zone defines a contorted Wadati-Benioff zone that dips to the north in the western end under Hindu Kush but dips southward at the eastern end of the zone under Pamir (Lukk & Nersesov, 1965; Lukk & Vinnik, 1975; Billington *et al.*, 1977). The opposing dips and an increase of seismicity where the two segments meet, imply that the zone consists of two distinct slabs with opposing directions of subduction (Fan *et al.*, 1994), but the possibility of a single contorted slab cannot be ruled out (Billington *et al.*, 1977). On the basis of the low seismic velocities in the upper mantle, Roecker (1982) concluded that the upper part of the Hindu Kush zone involved subduction of continental lithosphere and several studies (Burtman & Molnar, 1993; Fan *et al.*, 1994) have proposed that the Pamir zone is also composed of subducting continental lithosphere. On the other hand the evidence of high velocities associated with the Pamir seismic zone (Vinnik & Lukk, 1974; Lukk & Vinnik, 1975; Vinnik *et al.*, 1977) and a high velocity slab associated with the Hindu Kush seismic zone (Mellors *et al.*, 1995), may be evidence for subduction of oceanic lithosphere in deep part.

In Figure 10, the location of Indus suture zone, the geological features and the contours of isodepth mantle hypocenters are shown. Figure 11 shows the same contours in Figure

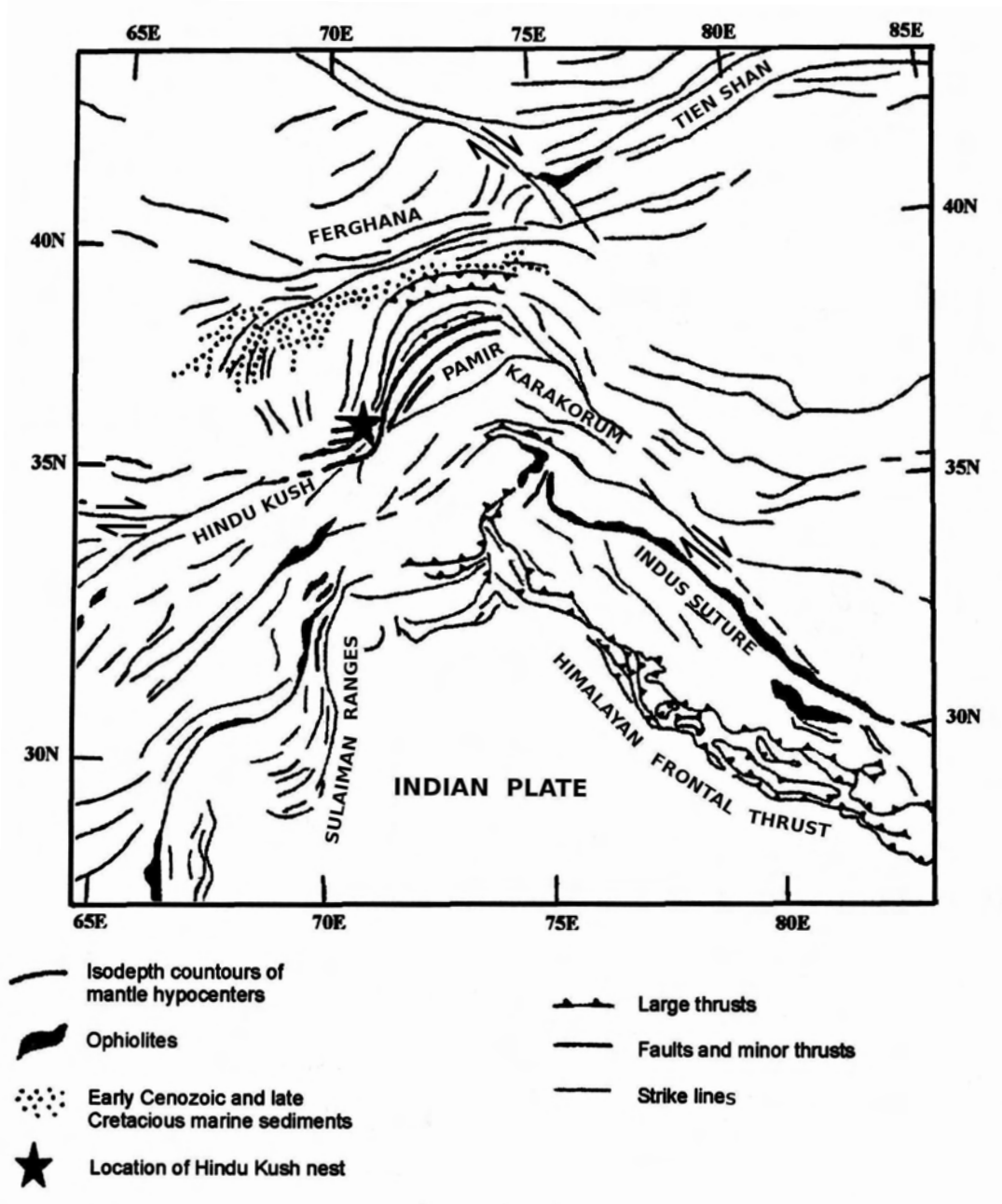


Figure 10: Map of geological features around Hindu Kush area and isodepth contours of mantle seismicity in Hindu Kush- Pamir area as heavy line.(from Billington *et al.* (1977))

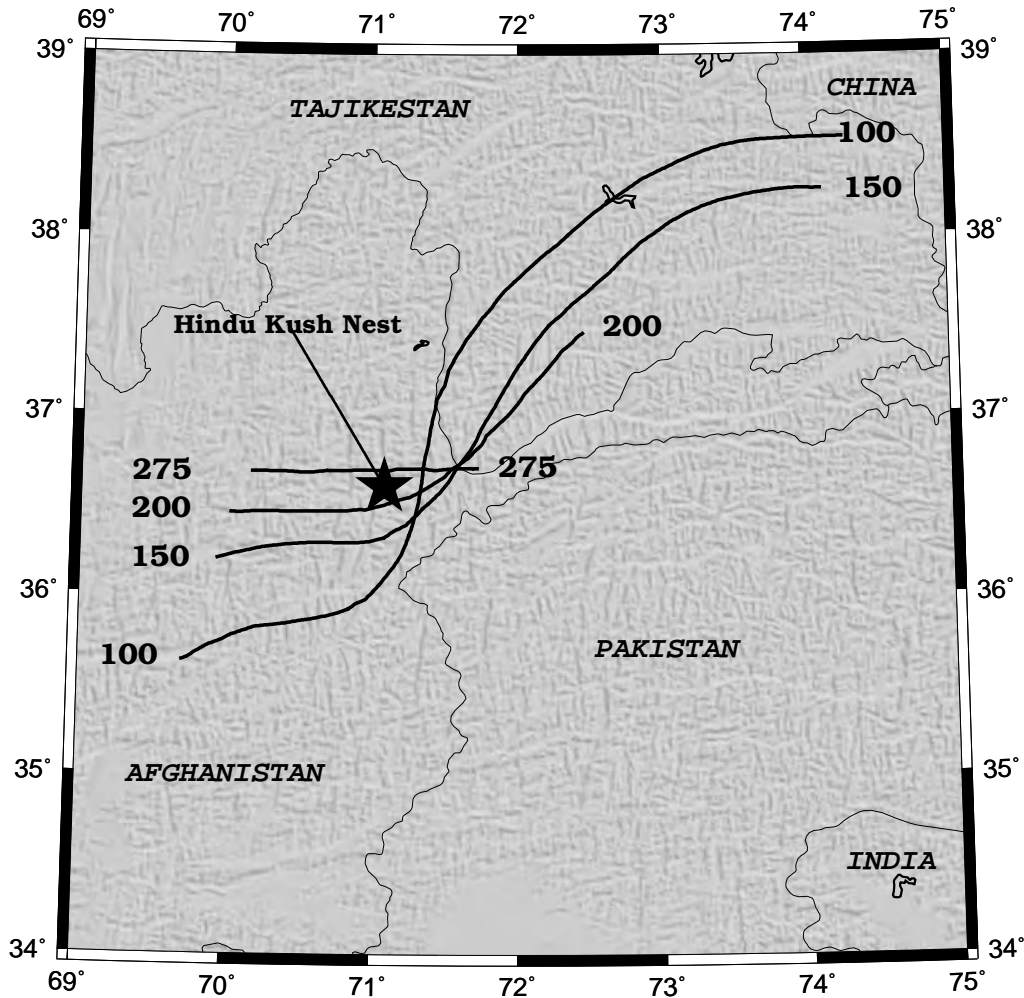


Figure 11: Isodepth contours of mantle seismicity in Hindu Kush- Pamir area in larger scale; the Hindu Kush nest is located in west of maximum curvature of the contours.(regenerated from original form of Billington *et al.* (1977))

10 at the top of the inclined seismic zone in the Hindu Kush and Pamir area. The nest in the Hindu Kush area is located at the west of the maximum curvature of these contours.

So, in general, we can say that all three nests are located in areas with very complex tectonic regimes in which collision between several plates is one of their characteristics. These nests all located in old slabs. Another feature that can be observed in the area of the nests is the curved surface expression of the subduction zone (Figures 2a,3a and 4a).

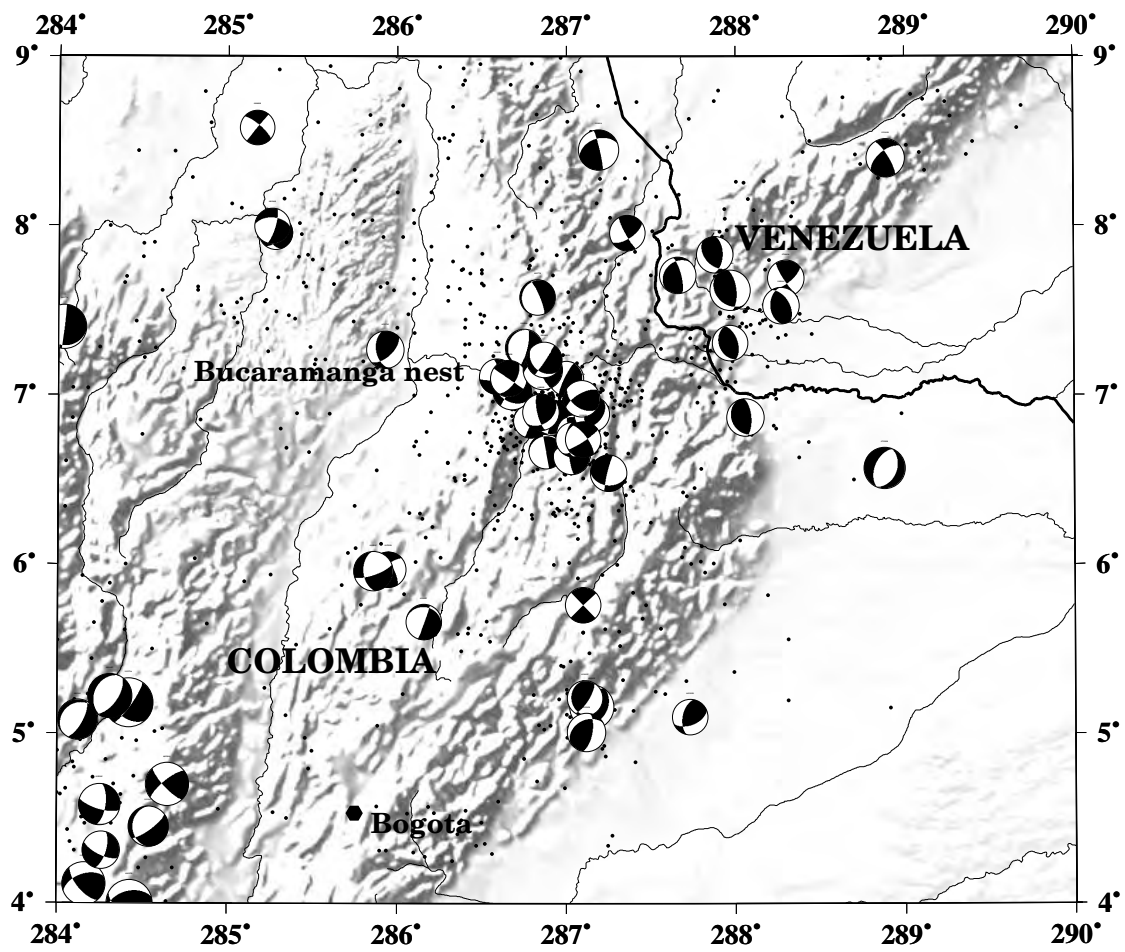


Figure 12: Central Moment tensor solution based on Harvard CMT catalog from 1976-2003 in Bucaramanga nest and its surrounding area.

#### 1.3.4. Focal mechanism of events in the nest area

To develop our understanding about the stress regime governing the areas around and inside the nests, investigation of focal mechanism of the events can be a useful tool so we will review the fault plane solutions for the three nests.

In the Bucaramanga, based on local data, Schneider *et al.* (1987) found an extreme variation in focal mechanisms of micro earthquake ( $M_b \leq 4.3$ ). Pennington (1981) reported focal mechanisms for events inside the nest based on teleseismic data. The majority of the focal mechanisms in his research show reverse faults. Figure 12 shows the fault plane solutions of earthquakes in Bucaramanga region based on Harvard CMT solutions. The reported focal mechanisms for the nest area are mostly reverse or strike slip with a reverse component.

The CMTs of moderate and strong intermediate depth earthquakes in Vrancea region show reverse faulting. This is also the case with small events which have the orientation of principal axes similar to all strong and most moderate earthquakes of a similar depth interval from this region (Gephart & Forsyth, 1984; Oncescu, 1986, 1987; Radulian *et al.*, 2000).

Figure 13, shows the focal mechanisms that have been reported by Harvard CMT solutions. This reported mechanisms show reverse faulting in the area of the nest.

In Hind Kush seismic zone, where we believe the major nest is located, most of reports (Billington *et al.*, 1977; Isacks & Molnar, 1971; Ritsema, 1966; Shirokova, 1959; Soboleva, 1968, 1972; Stevens, 1966; Nowroozi, 1972; Chatelain *et al.*, 1980) believe that the focal mechanism solutions indicate thrust faulting. Figure 14 shows the fault plane solution of events based on Harvard CMT solution of Hindu Kush nest and its surrounding area. Clearly most earthquakes have reverse mechanism.



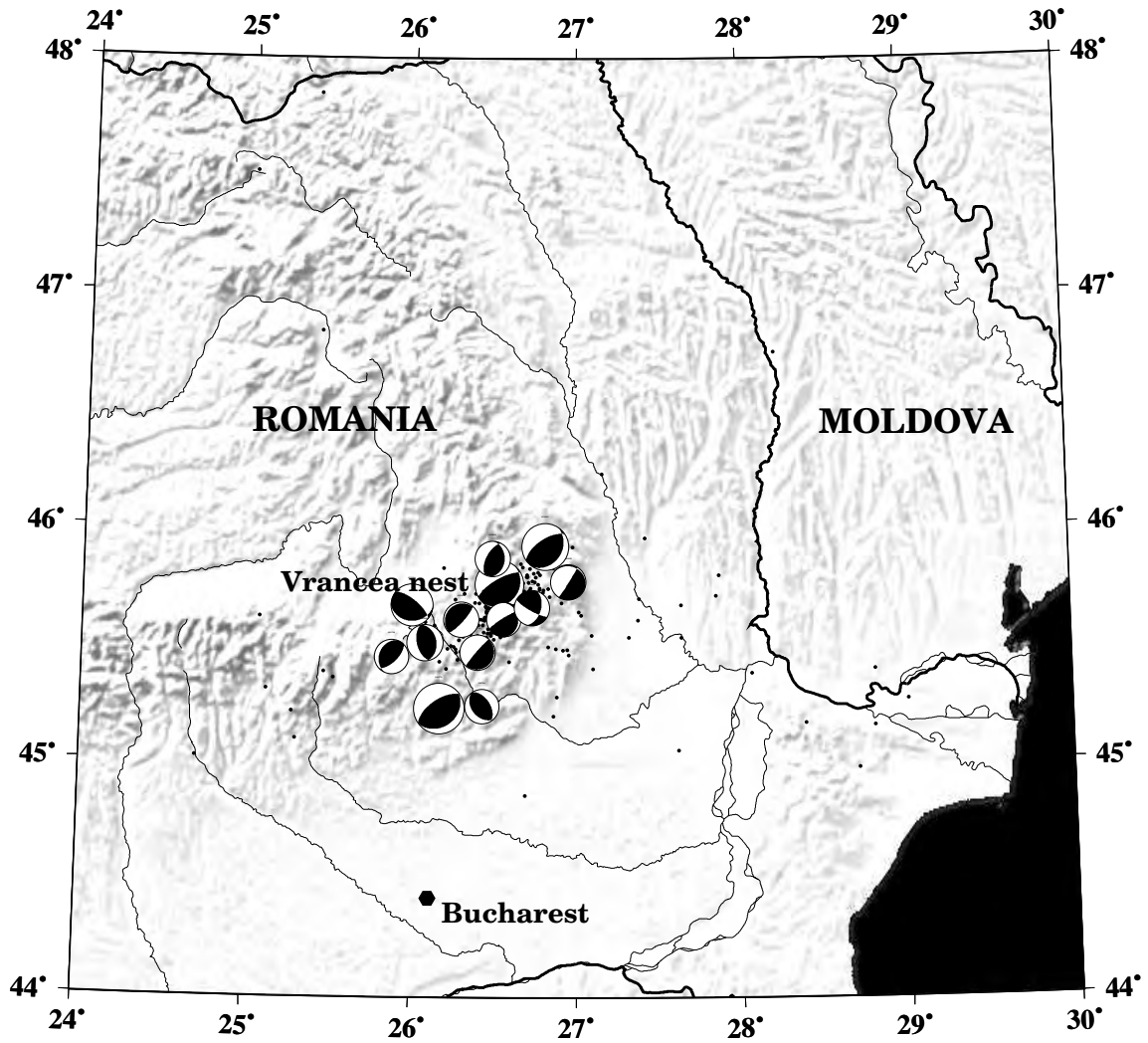


Figure 13: Central Moment tensor solution based on Harvard CMT catalog from 1976-2003 in Vrancea nest and its surrounding area.

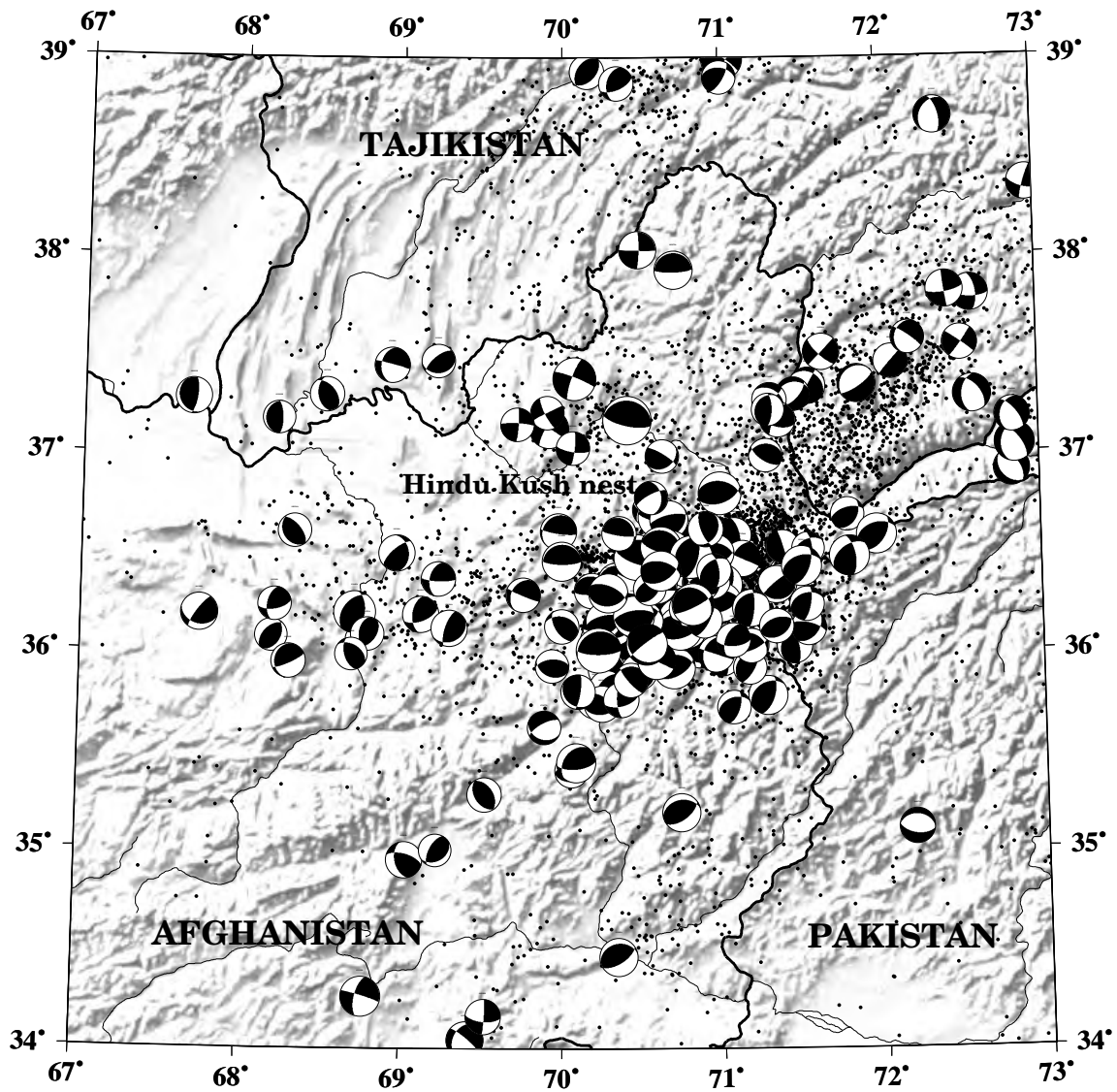


Figure 14: Central Moment tensor solution based on Harvard CMT catalog from 1976-2003 in Hindu Kush nest and its surrounding area.

### 1.3.5. Possible origins of known nests

Much effort has been put into the investigation the physical reason behind the existence of these nests without reaching any definite explanation. In this section we will review some of the suggested explanations.

The most favoured explanation for the Bucaramanga nest is related to the generation and migration of fluid (or to dehydration reactions), which is accompanied by phase changes. This might be caused by subduction of a buoyant feature such as an oceanic ridge or island arc, as suggested by Pennington (1981). This means that the region is weakened by active fluid migration and mobilized by the heating and shearing along the subducting slab (Shih *et al.*, 1991; Schneider *et al.*, 1987; Van der Hilst & Mann, 1994). On the other hand, the existence of a complex stress field near the contact of the Marcaibo and a redefined Bucaramanga slab (Figure 7) in the upper mantle, as has been suggested as a possibility for nest creation by Van der Hilst & Mann (1994), cannot be ruled out.

In the Vrancea nest, most studies favor a process of detachment of the slab (e.g. Sperner *et al.* (2001); Giunchi *et al.* (1996); Radulian *et al.* (2000)). The absence of intermediate depth seismicity in the northern part of the Carpathians indicates that this regional continental collision was followed by slab detachment. Corresponding to collision in the northern Carpathians, detachment also started in the north and propagated towards the south (Figure 9) and, today, the last slab fragment hangs beneath the south-eastern bend of the Carpathian arc exactly where the Vrancea nest is located (Sperner *et al.*, 2001). However in this area, in spite of the high level of activity at intermediate depth, no clear surface deformation can be seen (Radulian *et al.*, 2000). In general, the Vrancea earthquakes are unlikely to be produced in a passively sinking slab without any mechanical coupling to the overlying crust. Some kind of coupling is necessary to cause strong earthquakes inside the slab, but the non-existence of a slab-pull-related crustal

stress field indicates that this coupling is a 'soft' one (i.e. not strong enough to transfer slab-pull forces to the overlying crust).

Many authors (Billington *et al.*, 1977; Isacks & Molnar, 1971; Khalturin *et al.*, 1977; Nowroozi, 1971, 1972; Santo, 1969) have suggested that the Hindu Kush seismic zone is a manifestation of subducted oceanic lithosphere, possibly remnants either of the Tethys Ocean or of a marginal inter arc basin. Santo (1969) mentioned that the V shaped zone of seismicity suggested that two lithospheric layers had been under thrust from different directions at the same place. Since there is less activity in the upper crust in Hindu Kush nest, the hypothesis that Hindu Kush intermediate seismic activity is caused by the descent of a detached slab of lithosphere cannot be ruled out (Chatelain *et al.*, 1980). On the other hand, Vinnik *et al.* (1977) believe that the effectively rigid body of slab in the area is surrounded by softer material and is subjected to tectonic stresses, which are concentrated at eastern branch of subduction, leading to the observed seismicity in the nest area. The precise origin of this stress is not clear, but it appears to be mainly horizontal compression and probably associated with the main compressive forces in the Himalaya fold belt.

So, in general, there is no unique explanation for the possible origin of nests in the Bucaramanga and the Hindu Kush, but the seismicity of the Vrancea nest has been related to the process of detachment in that area.

### **1.3.6. Overall view**

By comparing seismicity, tectonics and earthquake focal mechanism in the area of the three nests, we find some common features between them, even though they are located far away from each other in a different tectonic plates. Remember that an intermediate or deep nest is defined, as the primary criteria, as a site of high concentration of continuously occurring intermediate or deep earthquakes. The smallest nest is Bucaramanga, the deepest is Hindu Kush. The 'b' value for all nests is nearly 'normal'. Comparing

the seismicity normalized to the volume, the activity in the Bucaramanga nest is much higher than in the two other nests. All three nests have more or less the same maximum earthquake size (Table 1) in the last 36 years so it seems that the nest environments have similar strength. All nests are located in a old subducted slab and the dip of subduction is vertical (the Vrancea and the Hindu Kush) or changes to near vertical (the Bucaramnga). The most common focal mechanism is reverse faulting, although other mechanisms can be observed, especially in the Bucaramanga. All nests are located in areas that are tectonically distorted. In Bucaramanga this may be caused by a convergent regime between three different blocks. In Vrancea it may be due to rotation of two adjacent blocks in opposite directions and in Hindu Kush there might be collision of two plates from opposite directions. There are no active volcanoes in these areas.

Although all the three nests have some similarities, there is no single clear evidence of the cause for the stress concentration leading to the high seismicity concentration. There is no evidence that a detached slab or relic subduction zone in itself should cause a high stress concentration or a particularly fractured environment. It seems more likely that the distorted subduction of possible relic plates, at particular depths, will create the right condition for high stresses, which coupled with the deformed, possibly fractured plates, then is responsible for the concentration of seismic events. Nevertheless, the common features of the nests might be used to identify other nests and thereby accumulate more evidence, which might lead to a better explanation of the cause of the nests.

#### **1.4. Part II. Possible intermediate or deep nests**

There are some suggestions about other possible nests around the world. For example, Tryggvason & Lawson (1970) indicated that some dense sources of intermediate and deep events in Burma and Italy might be nests. Also, Schneider *et al.* (1987) suggested that some clusters of events in Fiji, Ecuador and Chile-Argentina border may be nests. In this part, we will use the common criteria for the three well known nests to evaluate if

the possible nests can be considered nests like Bucaramanga, Vrancea and Hindu Kush. There is little published material about these possible nests and the comparison will therefore be based on global data. This cannot be conclusive since some nests may not be visible using global data.

#### **1.4.1. Fiji**

Schneider *et al.* (1987), indicated a possible nest of earthquakes in Fiji based on Isacks *et al.* (1967). In general, deep earthquakes in this area do not form either aftershock sequences or swarms of the types commonly observed in series of shallow shocks throughout the world, but a small percentage of the deep earthquakes cluster in the form of multiple events, i.e., small numbers of events closely grouped in space and time (Isacks *et al.*, 1967). What they have suggested was not a nest of events but all multiple events.

We have tried to cover all reported multiples in their research to find out whether they can be recognized as a possible nest or not. Among the multiples, at 22.2°S and 179.5°W, we find seismicity that may indicate a possible nest. Figure 15a, b show the possible nest in map and 3D view based on the ISC database. This possible nest has dimensions of about 90 km in N-S and 50 km in E-W directions and confined to depths between 570-620 km. Looking at the seismicity of this possible nest, based on ISC data, shows that the earthquakes occur in a continuous mode. The concentration of earthquakes in the area of the possible nest relative to surrounding area can be observed (Figure 15a). The b-value in the area of the possible nest is 1.73, with threshold magnitude of  $M_b=4.4$ , the maximum magnitude is 6.1 ( $M_b$ ) and the maximum in surrounding area (70 km away from the nest in every direction) is 5.5 ( $M_b$ ).

According to Isacks *et al.* (1967), the possible nest is located at the area of events with depths more than 450 km, in a place where some distortion in the earthquake zone can be observed. The rate and the maximum magnitude are similar to the other nests. The Focal mechanism in the area of the nest shows mostly reverse and strike slip with reverse

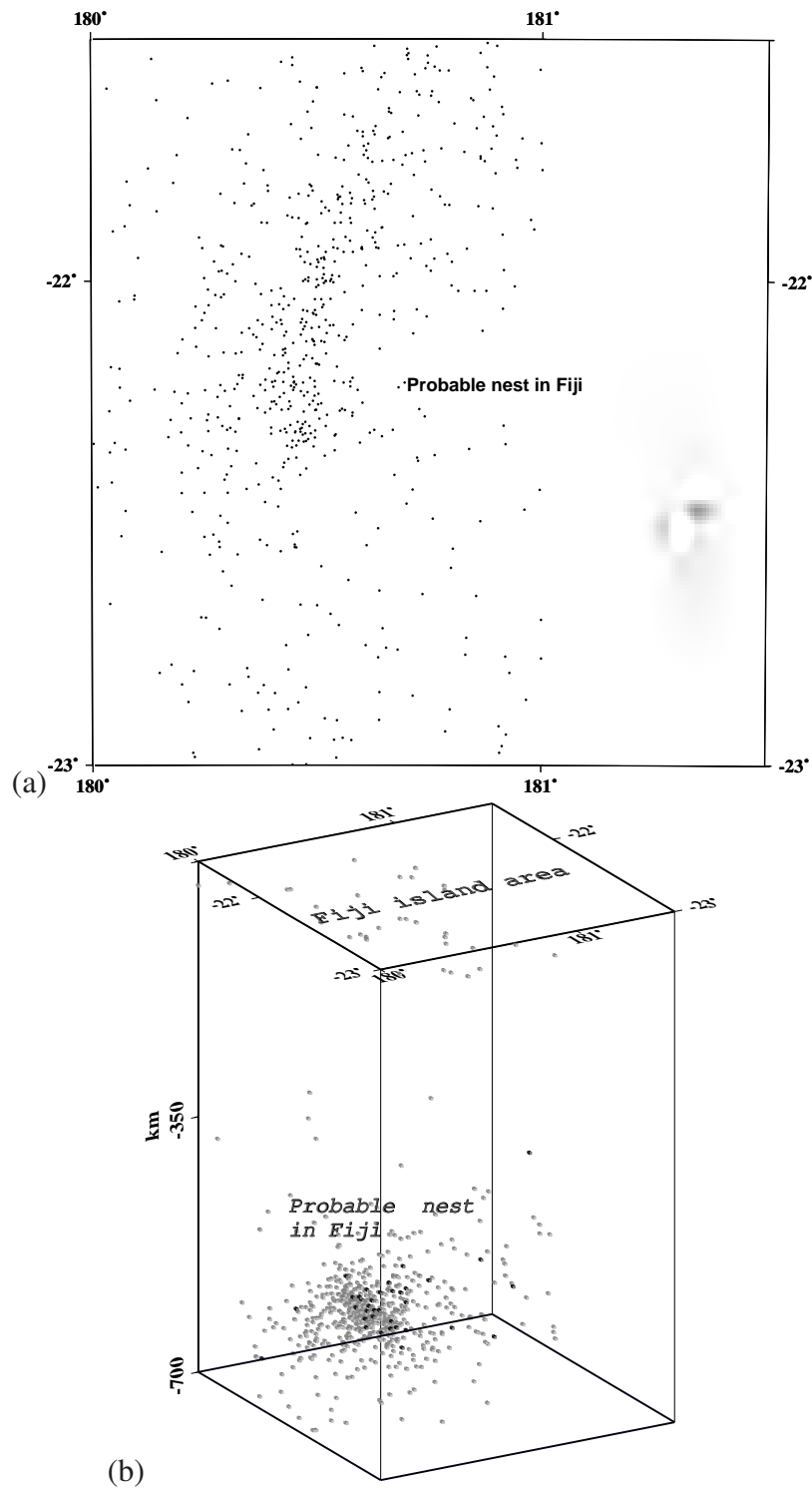


Figure 15: (a) Map and (b) 3D view of Fiji possible nest based on ISC database from 1964 to the end of November 2000. The black events are relocated data based on Engdahl & Villasenor (2002).

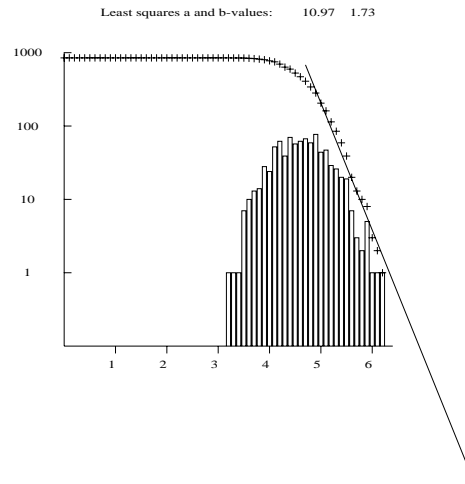


Figure 16: The Gutenberg- Ricjter diagram for Fiji nest.

component faulting based on Harvard CMT solution (Figure 17), which is strange for deep earthquakes, although some normal mechanism are observed in the nest area.

#### 1.4.2. Chile-Argentina

Based on Sacks *et al.* (1966), there is a nest of intermediate depth events in the Chile-Argentina border in Socompa area, which has a famous volcano with the same name. This possible nest may be in a group of nests close to volcanoes with known mechanism as explained in the introduction, but as its origin is not known, we tried to check for the same criteria that we have observed for the other nests. Schneider *et al.* (1987) have suggested that the nest is close to Chile-Argentina border at  $24^{\circ}\text{S}$  and  $67.5^{\circ}\text{W}$  in a depth between 200-300 km. We have tried to look at this area based on the ISC data.

Figure 18a and b show the possible nest area in map and 3D view. It is seen that the dimensions of this nest is 80 km in N-S, 60 km in E-W directions and confined to depths between 168 - 220 km. The area of the possible nest has concentrated activity relative to the surrounded area (Figure 18a). The occurrence of events is continuous. Considering  $M_b=4.4$  as a threshold magnitude, the b-value in the area is 1.35 (Figure 19).

The maximum observed earthquake has  $M_b=6.1$  in the ISC database inside the nest and  $M_b=5.1$  in the area around the nest. The reported focal mechanisms in the Harvard CMT



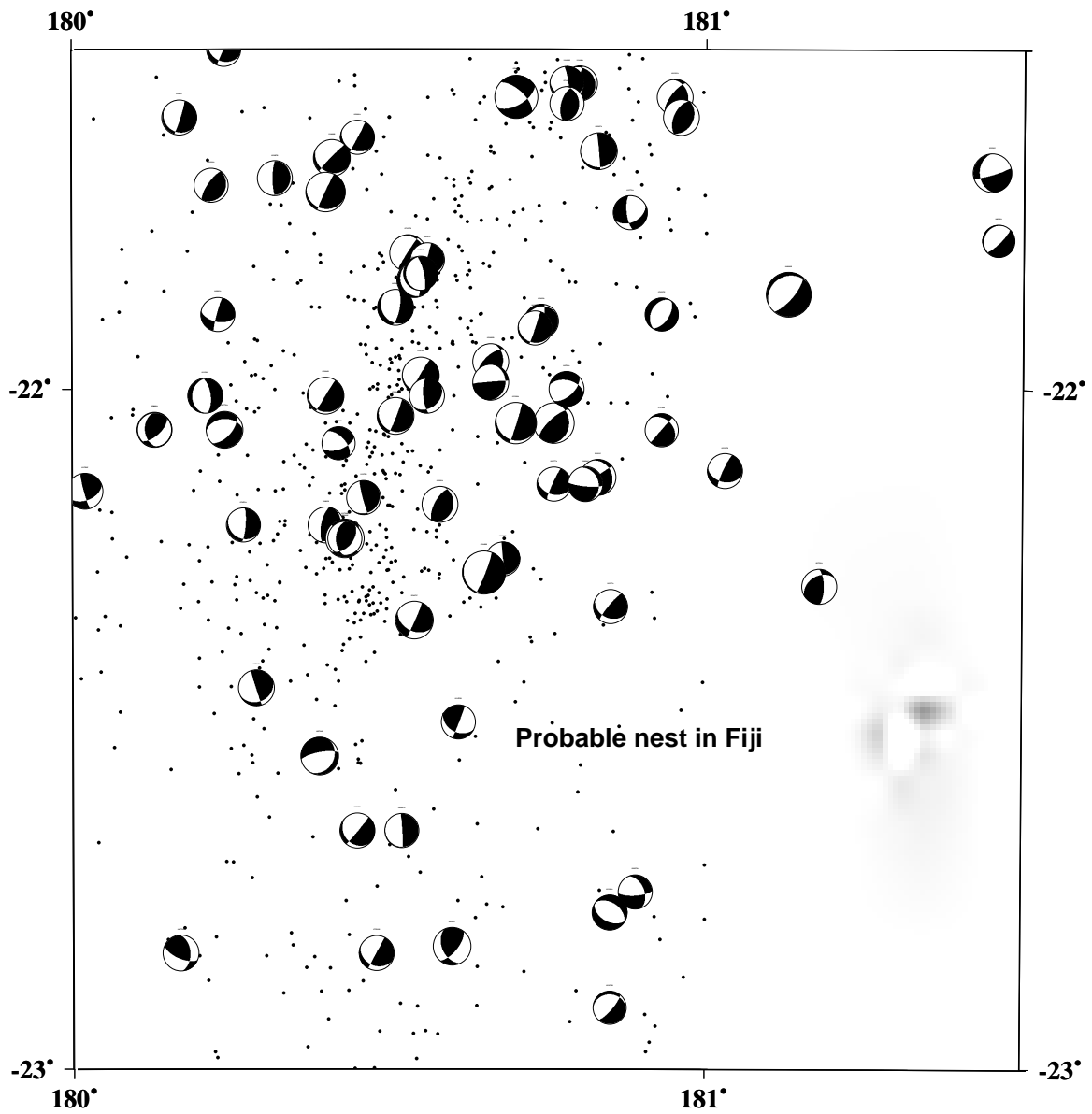


Figure 17: Focal mechanism of events inside the possible nest in Fiji and its surrounding based on Harvard CMT catalogue.

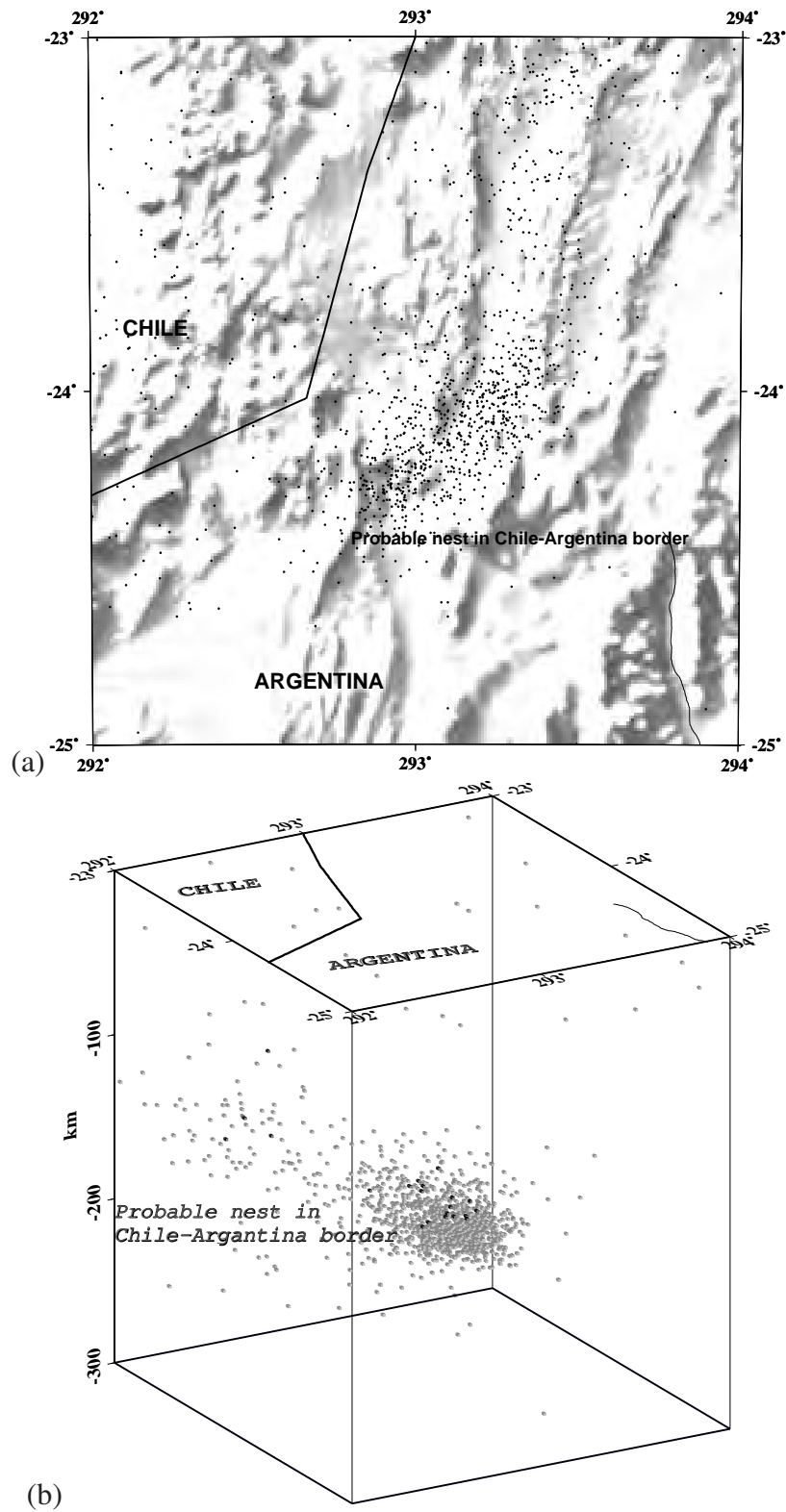


Figure 18: (a) Map and (b) 3D view of Chile-Argentina possible nest based on ISC database from 1964 to the end of November 2000. The black events are relocated data based on Engdahl & Villasenor (2002).

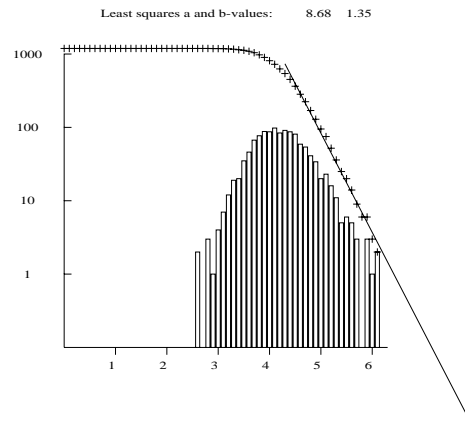


Figure 19: The Gutenberg- Richter diagram for Chile-Argentina nest.

catalog show normal faulting in this area (Figure 20).

### 1.4.3. Ecuador

Schneider *et al.* (1987) suggested that there may be a possible nest in Ecuador at  $1^{\circ}\text{S}$  and  $78^{\circ}\text{W}$  between 150-200 km depth, which cannot be observed clearly with global data. The Cotopaxi volcano in Ecuador located at  $0^{\circ}40' \text{ S}$  and  $78^{\circ}26' \text{ W}$  and may indicate that the nest has a volcanic origin as mentioned in the introduction, However, this is uncertain.

Using ISC data, this possible nest is located at  $1.5^{\circ}\text{S}$  and  $78^{\circ}\text{W}$  (Figure 21a, b). The dimension in the N-S direction is 70 km, in W-E direction is 60 Km and in the depth is confined between 150-200 km. Considering  $M_b=4.4$  as the threshold magnitude, the b-value for this area is 1.14 (Figure 22).

The maximum observed magnitude in 36 years catalogue of ISC data in the nest area is 5.9 ( $M_b$ ) and in the surrounding area of the nest is 5.5 ( $M_b$ ). Figure 23 shows the focal mechanisms of earthquakes in the area of the nest based on Harvard CMT solution, which are mostly normal faulting.

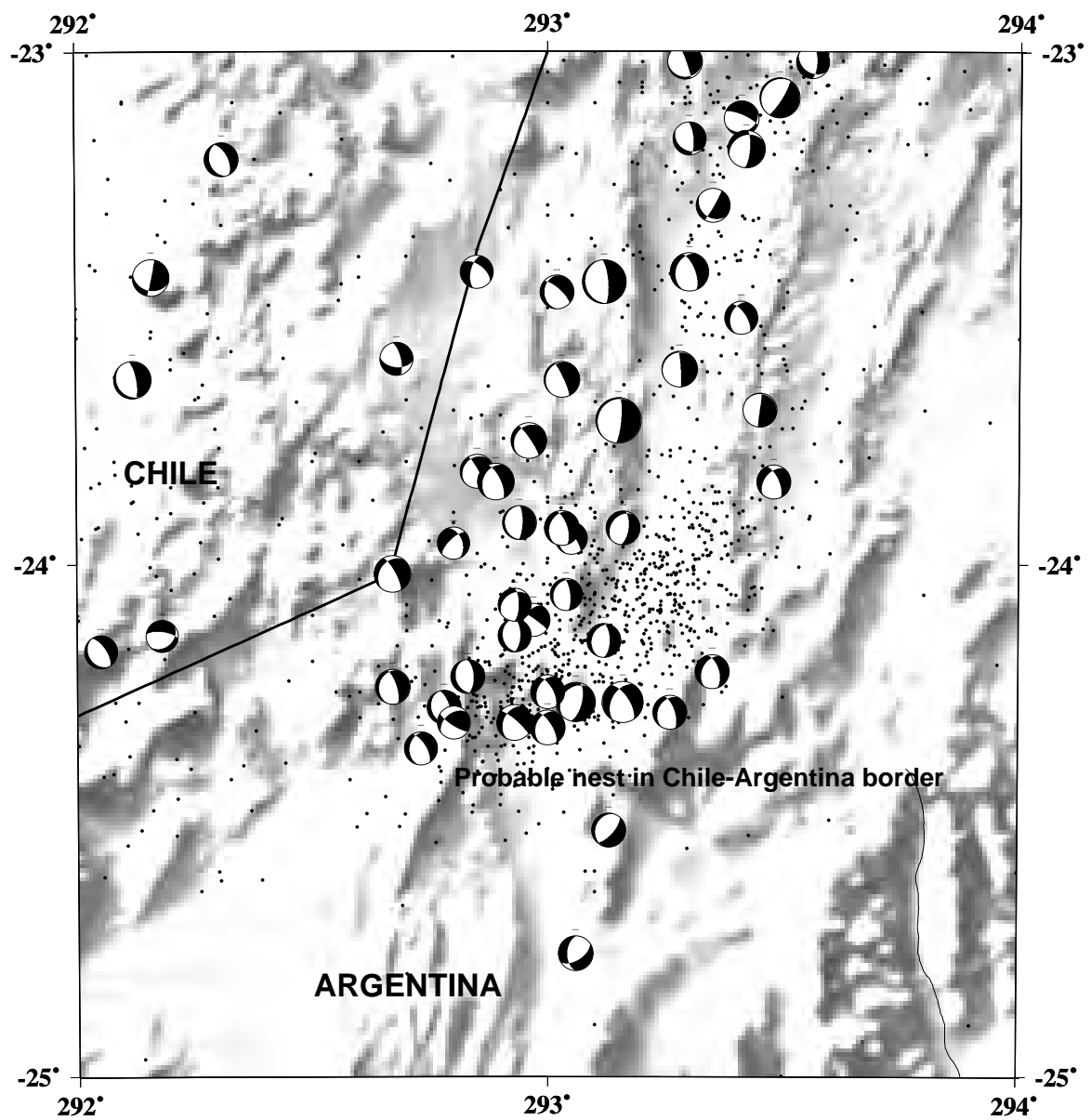


Figure 20: Focal mechanism of events inside the possible nest in Chile-Argentina border and its surrounding based on Harvard CMT catalog.

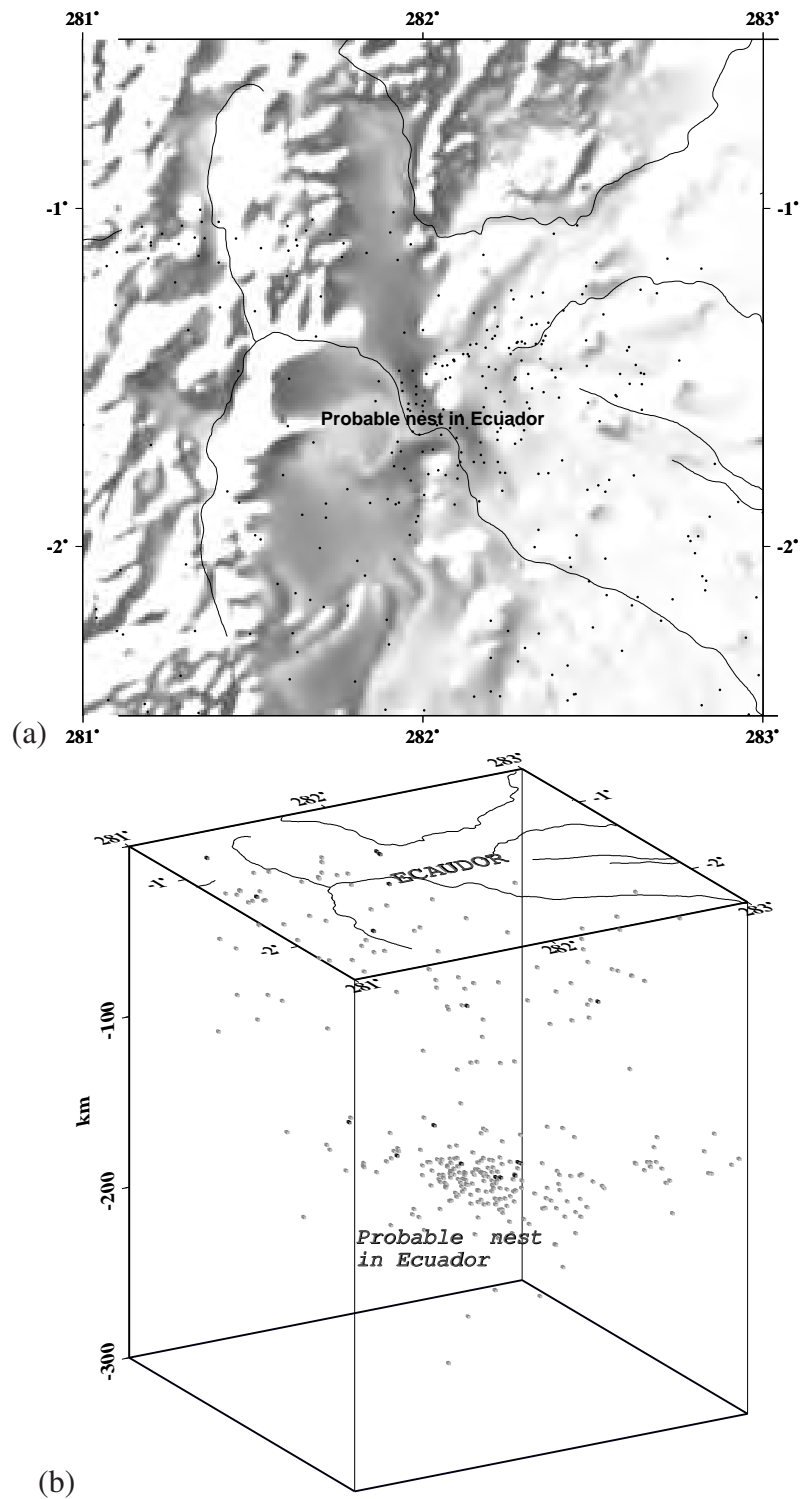


Figure 21: (a) Map and (b) 3D view of Ecuador possible nest based on ISC database from 1964 to the end of November 2000. The black events are relocated data based on Engdahl & Villasenor (2002).

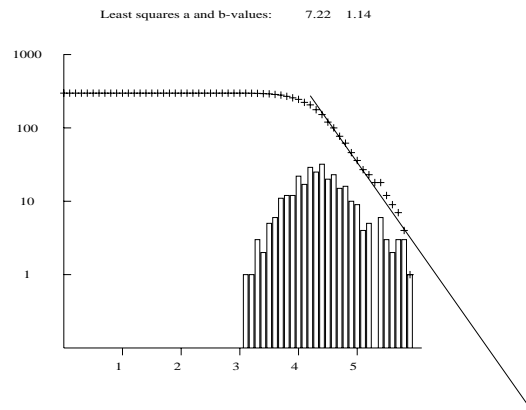


Figure 22: The Gutenberg-Richter diagram for the Ecuador nest.

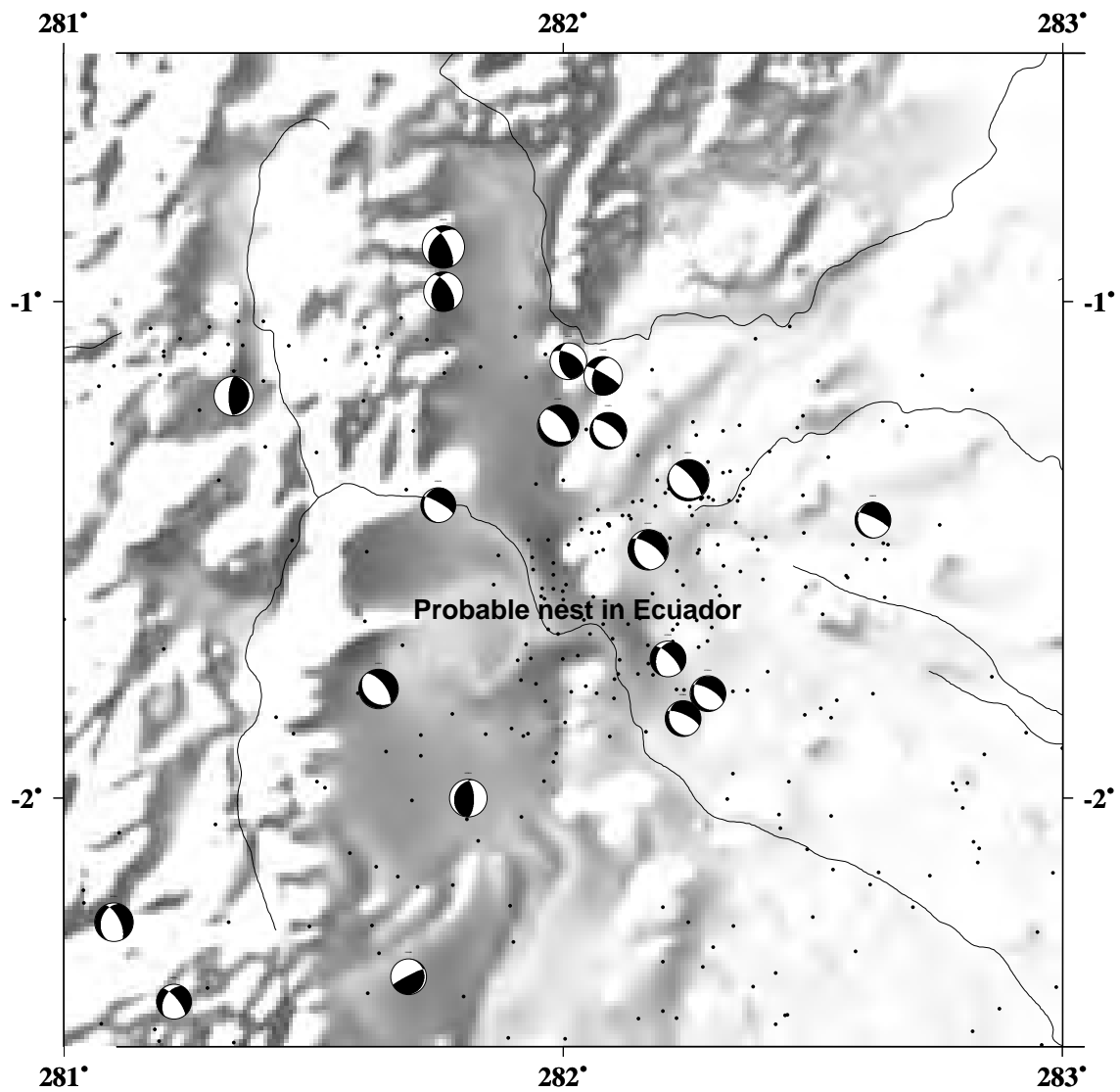


Figure 23: Focal mechanism of events inside the possible nest in Ecuador and its surrounding based on Harvard CMT catalog.

#### 1.4.4. Burma and Italy

Tryggvason & Lawson (1970) suggested a possible nest at 24°N and 95°E in Burma, where we observe the Indian plate under thrusts the southeastern Asian plate and another possible nest at 39°N and 15°E in Italy, where the subduction of the African plate underneath the Eurasian plate occurs. Based on ISC data there is no evidence for existence of any cluster of events at these sites. Of course, it is possible that the nest is not seen using the global data due to a generally lower magnitude. However, in the previous cases, the nest had comparable maximum magnitudes and seismicity rates, so the suggested possible nests in Italy and Burma would not be comparable with the 'standard' nests. Thus in the suggested location in Burma and Italy there is no evidence for existence of nests based on global data.

#### 1.4.5. Overall view

The general information about the possible nests is summarized in Table 2. Based on global data, among these possible nests, the biggest volume belongs to the Socompa possible nest in the Chile-Argentina border, which is also the most active nest compared to the others (Table 2). The largest reported earthquakes in these possible nests have more or less the same range of magnitude (5.9 - 6.1  $M_b$ ) as confirmed known nests. The strongest events take place in the possible nest in Fiji. The observed focal mechanism for the nest area is mostly reverse faulting in Fiji and normal faulting in Ecuador and Chile-Argentina border. Although the number of strong earthquakes in Fiji is more than the for Ecuador and Chile-Argentina nests, the b-value here is larger than the other two possible nests.

Global data does not show any evidence for existence of nests in Italy and Burma, but their existence cannot be ruled out, because may be they are not recognizable with the global data.

Table 2: Summary of observed Seismicity in the possible nests.

Nest	Fiji	Chile-Argentina	Ecuador
Location	22.2°S, 179.5°W	24°S, 67.5°W	1.5°S, 78°W
Depth(km)	570-620	168-220	150-200
Size(ISC)	90×50×50	80×60×100	70×50×50
Normalized Volume ( $V/V_{Hindu\ Kush}$ )	0.47	1.0	0.36
Total number of events	277	776	173
Events with $M_b > 4.8$	156	102	28
Number of events with $M_b > 4.8$ per $V_N$	332	102	77
Average number of events with $M_b > 4.8$ /month	0.36	0.23	0.06
b value	1.73	1.35	1.14
Largest reported event ( $M_b$ )	6.1	6.1	5.9
Largest reported event ( $M_b$ ) in the surrounding area	5.5	5.1	5.5
Seismic moment release rate inside the nest (Nm/Y)	2.22E+23	1.55E+23	1.19E+23
Seismic moment release rate around the nest (Nm/Y)	5.22E+22	1.71E+23	8.10E+21



## 1.5. Conclusions

Reviewing the seismicity, tectonic, focal mechanism and possible origin of known nests in Colombia (Bucaramanga), in Romania (Vrancea) and in Afghanistan (Hindu Kush) reveal that all these nests are located in old subduction zones (relic subduction). The dips of these slabs are vertical (in Vrancea and Hindu Kush) or changes to near vertical (Bucaramanga). The majority of focal mechanisms of earthquakes are reverse faulting. Another common point between all these nests is their locations in a regime of complex tectonics and close to distorted tectonic features. Several studies have tried to find a physical reason for the existence of nests, but this is still more or less a mystery. The most known mechanism is the mechanism of a detaching slab for Vrancea, but the Vrancea earthquakes are unlikely to be produced in a passively sinking slab without any mechanical coupling to the overlying crust. Some kind of coupling is necessary to cause strong extension inside the slab, but the non existence of a slab-pull-related crustal stress field indicates that this coupling is not strong enough to transfer slab pull forces to the overlying crust. The candidates for driving mechanism in Bucaramanga nest are dehydration reactions, fluid migration or a complex stress field in the nest. In Hindu Kush, the distorted subduction or collision of two slabs from opposite directions, can be a driving mechanism for existence of a nest. There are also some other possible nests, like the possible nest in Fiji, in Chile-Argentina border and in Ecuador, which can be recognized by global data. All them are located in a subducted slab. One possible mechanism for nests in Ecuador and in Chile-Argentina border can be volcanic, because both of these nest are in a few 10's of kilometres of known volcanoes. There are some similarities between the size of possible nests and known nest. For example the possible nest in Socompa, in Chile-Argentina border has the same size as the Hindu Kush nest. Among all of these nests (including possible nests), most of the big earthquakes (in Mb magnitude) take place in Fiji, followed by Vrancea. The Bucaramanga nest is the most active by volume.

It seems that the possible nests in Chile-Argentina and Ecuador experience a stress regime different from what can be observed in Bucaramanga, Vrancea, Hindu Kush and Fiji (normal faulting versus thrust faulting). On the other hand, Bucaramanga, Vrancea and Hindu Kush nests plus the possible nest in Fiji are located in areas with distorted subduction. No active volcanos in the area of known nests can be observed and obviously the seismicity in the Fiji nest, at such a depth, cannot be related to volcanic activity. This is not the case for nests in Ecuador and Chile-Argentina, because both are close to volcanoes. More information is needed to reveal the most likely mechanism for all these nests.

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