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Seismicity, b - values and focal depth distributions of earthquakes in the Andaman-Nicobar Island region

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An analysis of seismic data of the Andaman-Nicobar Island region that lies between 4°-16°N and 90°-98°E has been made for the 1900-1982 period. A seismicity map has also been prepared for the aforesaid period. The major features of the seismicity of the region are well seen from this map. It shows a well-defined pattern almost parallel to the structural trend of the basin. The *b* values as determined from the earthquake frequency-magnitude relationship of Gutenberg and Richter are found to be in good agreement with the result obtained in northeast India. The depth-distance cross-sections, measured eastwards from 92°E at the latitudes 7°N, 9°N, 11°N and 13°N, have been made to understand the foci distribution and the nature of seismic zones and their geometry beneath the Island arc system. These seismic cross-sections reveal some interesting results on the oblique subduction of the Indian plate beneath the Andaman sea plate and rifting of the central Andaman through.

Seizmičnost, b-vrijednost i razdioba dubina žarišta potresa u otočnom području Andaman-Nicobar

Analizirani su seizmički podaci iz razdoblja 1900-1982. godine za područje otoka Andaman-Nicobar, koje se rasprostire između 4°-16°N i 90°-98°E. Također je za to razdoblje izrađena i karta seizmičnosti na kojoj su vidljiva glavna obilježja seizmičnosti toga područja. Uočljivo je da se hipocentri potresa grupiraju gotovo paralelno pružanjima struktura bazena. *b*-vrijednost određena prema Gutenberg-Richterovoj relaciji u suglasju je s rezultatima dobijenim za sjeveroistočnu Indiju. Radi upoznavanja razdiobe hipocentara te geometrije i svojstava seizmičkih zona, nacrtani su profili, usmjereni od 92°E na istok, na geografskim dužinama 7°N, 9°N, 11°N i 13°N.Oni ukazuju na kosu subdukciju Indijske ploče pod ploču Andamanskog mora i na pucanje središnje Andamanske depresije.

1. Introduction

During the last 15 years there has been much evidence that large earthquakes, occurring apparently at random in various seismic regions are, on long time scale, casually related and characterized by patterns of non-randomness in location, magnitude and time. These patterns when recognized with great reliability become important for evaluating the seismic potential, recurrence time and seismotectonic effect for a large earthquake in a specified region. Results of numerous studies have shown that the use of (1) the basic nature and mechanism of large earthquakes, (2) plate tectonics concepts and their relationship with large earthquakes and (3) the space-time-focal depth evolution of historical seismicity, provides an adequate framework for a further understanding of the tectonic deformation in a region.

The Andaman Sea, one of the most seismically active regions in the Bay of Bengal has now been considered as an actively spreading back-arc basin (Fitch, 1972; Lawver et al., 1976; Curray et al., 1979; Eguchi et al., 1979; Uyeda and Kanamori, 1979 and others). It has long been suspected that various tectonic phenomena associated with the trench-arc-backarc system have been responsible for several damaging earthquakes in the region. Of these the earthquakes of 26 June 1941 near Port Blair, 16 November 1962 near Diglipur and 8 February 1978 near Mayabhandar are worth mentioning. In essence, the occurrence of large earthquakes can be represented as a continuous physical process in which stresses gradually accumulate, due mostly to the plate motions and are suddenly released from time to time.

In view of increasing seismic activity in the Andaman Sea, this paper aims to study the following aspects : 1) spatial distribution of earthquake location, 2) *b*-value determination for a group of earthquakes in the frequency- magnitude relation and maximum likehood method of Aki and 3) space-time-focal depth distribution of earthquakes and identification of possible active seismic zones.

2. Seismicity

In plate tectonics, the multiple features characterizing the interaction of moving plates along their active boundaries are mostly associated with the occurrence of large earthquakes. Features such as the dip and length of a Benioff zone, the existence of seismic zones, volcanoes, the pattern of underthrusting plates, the presence or absence of active/inactive back-arc basins etc. specify the tectonic regimes under which large earthquakes occur. The type of motions along plate boundaries as well as the seismic slip rates are well reflected in the nature of earthquake faulting. This,

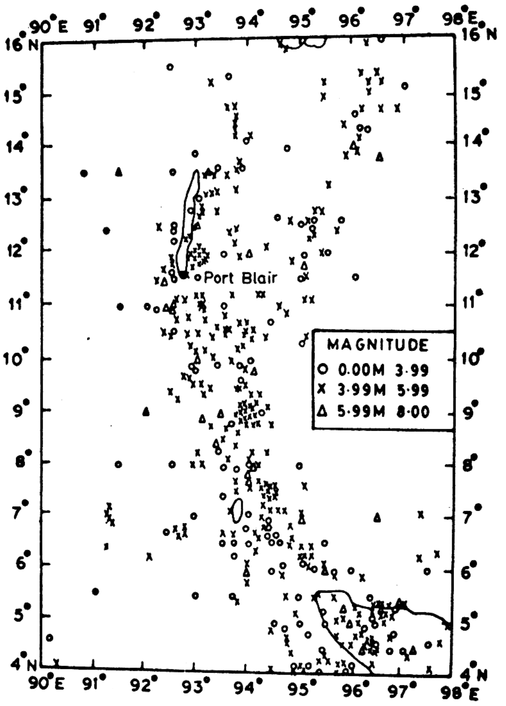

Figure 1. Seismicity map of Andaman-Nicobar Island region for the 1900-1982 period.

in other words, implies that from the nature of the tectonic stress regime and the earthquake history in a seismotectonic zone, regular patterns can be inferred for identifying regions of potential earthquakes. Thus the study of the seismicity of a region may be one of the most useful and important basic tools of gaining some insight into what should be expected in the future.

A seismicity map of the Andaman Sea lying between 4°N- 16°N and 90°E - 98°E has been prepared for the 1900-1982 period and is shown in Fig. 1. The sources of data have been taken from the following agencies :

1. Bulletin of the International Seismological Centre, U. K.,
2. Bulletin of the India Meteorological Department, New Delhi,
3. USGS magnetic tape file and
4. PDE Bulletins, NOAA.

In addition to these agencies, analysis of the records of the Port Blair observatory which is equipped with Benioff and Wood-Anderson seismographs, has also

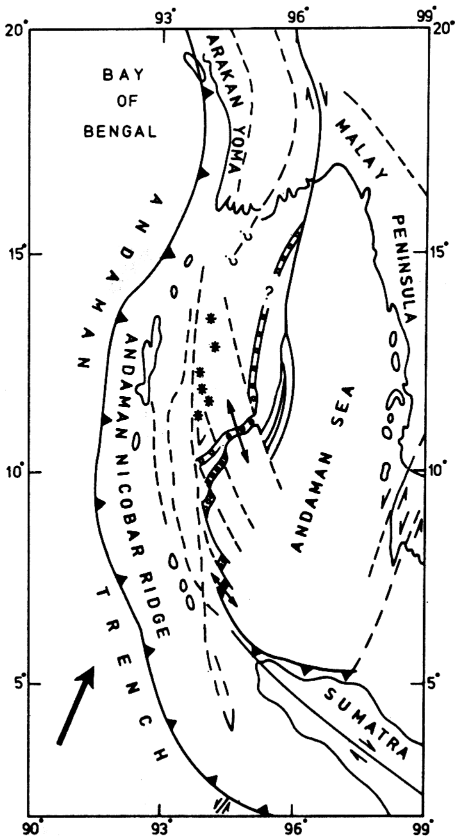

Figure 2. Schematic representation of the structural and tectonic elements of the Andaman-Nicobar island arc, the Andaman Sea and adjoining areas. Tectonic features are adopted from Gurray et al. (1979). Broken lines, asterisk and solid lines with sense of shear direction denote inactive faults, volcanoes and active faults respectively. Parallel lines with intervening circles and solid lines with solid triangles represent active spreading ridges and trench along which underthrust of Indian plate beneath the Andaman-Nicobar islands takes place. Solid bold arrow indicates the drifting motion of the Indian plate.

been included in the present work for assesment of local magnitudes. The major features of the seismicity of the Andaman Sea are well reflected from the epicentre plot as shown in Fig. 1. The seismicity shows a well defined pattern almost parallel to the structural trend of the area (Fig. 2). Shallow earthquakes are mostly common in this area although it is seen that the focal depths become deeper (exceeding 100 km) towards the eastern side and it is evident that the whole of the Andaman basin is seismically very active. However the seismicity is found to be restricted within a zone of 4° longitudinally (92.0°E - 96.0°E). Earthquakes occur in the region at depths ranging from very shallow (5 km) to about 230 km. In the Andaman Island the deepest earthquake occurred on 6 April, 1980 (13.13°N, 93.27°E, $d=119$ km) while in the Nicobar region it occurred on 12 April, 1973 (7.57°N, 95.05°E, $d=229$ km).These two events, located in the southern part of the Andaman Sea, are probably related to the oblique subduction of the Indian plate. The other redeeming feature of the seismicity map is that the 'interdeep' region is dominated throughout by earthquakes although earthquakes are common too, in the 'inner volcanic arc'. With the exception of a small cluster of earthquakes near 7°N, 91.3°E, the seismic belt is narrow in the south Andaman island and becomes wider northwardly. Broadly speaking, the seismicity map shows the presence of two linear seismic zones in the region. One is associated with the Andaman-Nicobar Island chain where active oblique subduction of the Indian plate takes place against the Andaman-Nicobar Island arc. This seismic zone is very intense, curvilinear in shape and extends from the north Andaman Island to the Sumatra Island. It is due chiefly to the shearing and compressional effect between the underthrusted Indian plate and overriding Andaman Sea plate. The other relatively narrow less intense shallow seismic zone is situated in the Andaman Sea. This seismic zone is oriented in NNE-SSW direction and associated with a relatively narrow back-arc spreading ridge in the Andaman Sea. It may be noted here that almost all of the greater magnitude earthquakes ($M>>5.99$) are associated directly with the subduction process of the Indian plate. This subduction process releases much energy in response to the mechanical coupling between the downgoing Indian plate and overriding Andaman plate in the island arc region. On the other hand the narrow, shallow and less intense seismic zone in close proximation with the back-arc ridge is mainly related to back-arc opening and characterized by low stress field.

3. *b* - values and frequency-magnitude relationship

Earthquake strain release pattern on a global scale suggests that relative variations of stress through time determined at the trench/subduction zones can very well be correlated with the observed b - values i. e. the negative slope of earthquake magnitude log-frequency graph. In 1957 Gutenberg and Richter presented an empirical equation describing the relationship between the number of earthquakes and magnitude. The commonly used form of the equation is

$$\log_{10} N = a - bM$$

where N is the number of earthquakes in a region per unit time in a particular magnitude (M) range $M+\mathrm{d}M$ and M-dM. The parameter of interest in this study is b-

Table 1. a nad b values in Andaman - Nicobar regions

Sl.No	Region	Type of magnitude	Data source	*a*	*b*	Remarks
1.	1° around Port Blair	M_L	IMD(1967-1974)	5.155	0.95	Using Gutenberg-Richter's Relationship.
2.	Andaman Nicobar	M_b	USGS(1964-1982)	8.53	1.35	
3.	Andaman Islands					
	a) 0-33 km focal depth	M_b	USGS(1964-1982)		1.05 ±0.15	Using max. likelihood method of Aki (1965)
	b) 33 km focal depth	M_b	USGS(1964-1982)		0.98 ±0.13	
4.	Nicobar Islands					
	a) 0-33 km focal depth	M_b	USGS(1964-1982)		0.95 ±0.15	-"-
	b) >33 km focal depth	M_b	USGS(1964-1982)		1.42 ±0.16	

value. If experimental laboratory work is correct the *b*-value is inversely related to stress in a qualitative sense.

Mogi (1962 a, b, c ; 1963 a,b) from a series of laboratory experiments showed that the *b*-value increased with the degree of heterogeneity of the sample and the degree of spatial variations in the stress distributions. Scholz (1968) improved on Mogi's method using various rock types to show that *b*-value decreased as stress was increased until fracture occurred. Several investigations have also examined the variation of *b*-value with time and in relation to stress for particular regions. Shilen

Table 2. Calculated recurrence interval for different magnitude

Magnitude (M_b)	Return periods (years)	Relation used
5.0	1.31	G-R
5.5	2.01	G-R
6.0	3.56	Aki
6.5	6.86	Aki
7.0	13.70	Aki
7.5	28.21	Aki
8.0	58.42	Aki
8.5	121.56	Aki

and Toksöz (1970) calculated the annual b-value for several regions and showed no significant b-value changes in time or between regions.

These interesting observations on the relationship b -value vs. stress conditions fascinates us to apply the earthquake frequency magnitude relationship of Gutenberg and Richter (1954) for a group of earthquakes in the Andaman-Nicobar Island region for determining the b-values and reccurrence interval for earthquakes of various magnitudes. Fig. 3 shows the plot of log N versus M_L and Mb in the region. For b-value studies all the data have been computed from the USGS and accordingly divided into two groups. In the first group, local magnitudes (M_L) have been determined from Wood-Anderson seismograms within 1° radius around Port Blair (11.59°N, 92.62°E), for the 1967-1974 period in order to asses the local stress concentration (for M_L values only, data were collected from the Port Blair observatory of IMD). In the second group all data from 1964-1982 (USGS) have been assigned body wave magnitudes (Mb) and divided into sub-groups i. e. 0-33 km and greater than 33 km focal depths. Here the b-value have been computed for these depth ranges in the Andaman and Nicobar regions by using the Gutenberg-Richter (G-R) relationship and maximum likehood method of Aki (1965). The maximum likehood estimate for a certain earthquake group which follows the G-R relationship is represented by the equation

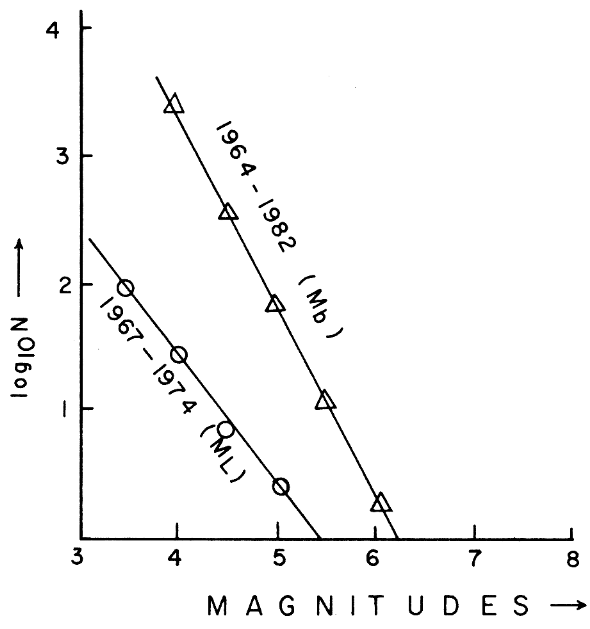

Figure 3. Earthquake frequency magnitude relationship in the Andaman-Nicobar Islands region.

$$b = 0.4343 / (M - M_o)$$

where M and M_o denote the mean and lower limit of magnitude from each earthquake group. The upper and lower limits of confidence of b for 95 % probabilty are $\pm$ 1.96/ $\sqrt{n}$ where n is number of earthquakes. The results are given in Table 1. It is seen that the value of b is 0.95 (M_L) and 1.35 (M_b) when determined from local magnitude and body wave magnitude respectively. This is found to be in good agreement with the results obtained for Shillong region of north-east India. Drakopoulos and Srivastava (1972) have shown that for Shillong region the b- value is 0.96 for local magnitudes and 1.39 for bodywave magnitudes. This probably suggests that in and around Shillong and Port Blair regions, character of local stress concentration may be of similar nature and higher b values indicate the presence of low stress condition, i. e. occurrence of smaller magnitude events are more prevalent in these two regions. The recurrence intervals for different magnitudes as determined from the G-R and Aki's relationship are shown in Table 2.

It is generally believed that there is an upper magnitude limit above which the G-R relation does not hold (Utsu, 1971, Cosentino et al., 1977). Above this limit, points on the magnitude log-frequency plot may deviate distinctly from the linear trend. In this study only events with magnitudes M_b = 6.5 are considered too large and in these cases b-values are determined from Aki's formula only (Table 1). The lowest magnitude chosen is M_b = 3.0 (or M_o = 3.0). If this limit is too small then the b-value calculated could be wrong. As a test of this limit and more detailed studies on the stress accumulation and energy release, b-values have been calculated depthwise for Andaman and Nicobar Islands separately using the body wave magnitude and Aki's relation (Table 1). However, in case of local magnitudes (M_L), differences in the considered time period and differences in considered area (too small)

Table 3. Circum Pacific b-values (after Carter and Berg, 1981)

Region	b-value
South America	0.80
Kermadec	0.97
Tonga	0.95
New Hebrides	0.80
Kuril	0.82
Kamchatka	0.95
W. Aleutians	0.84
E. Aleutians	0.88

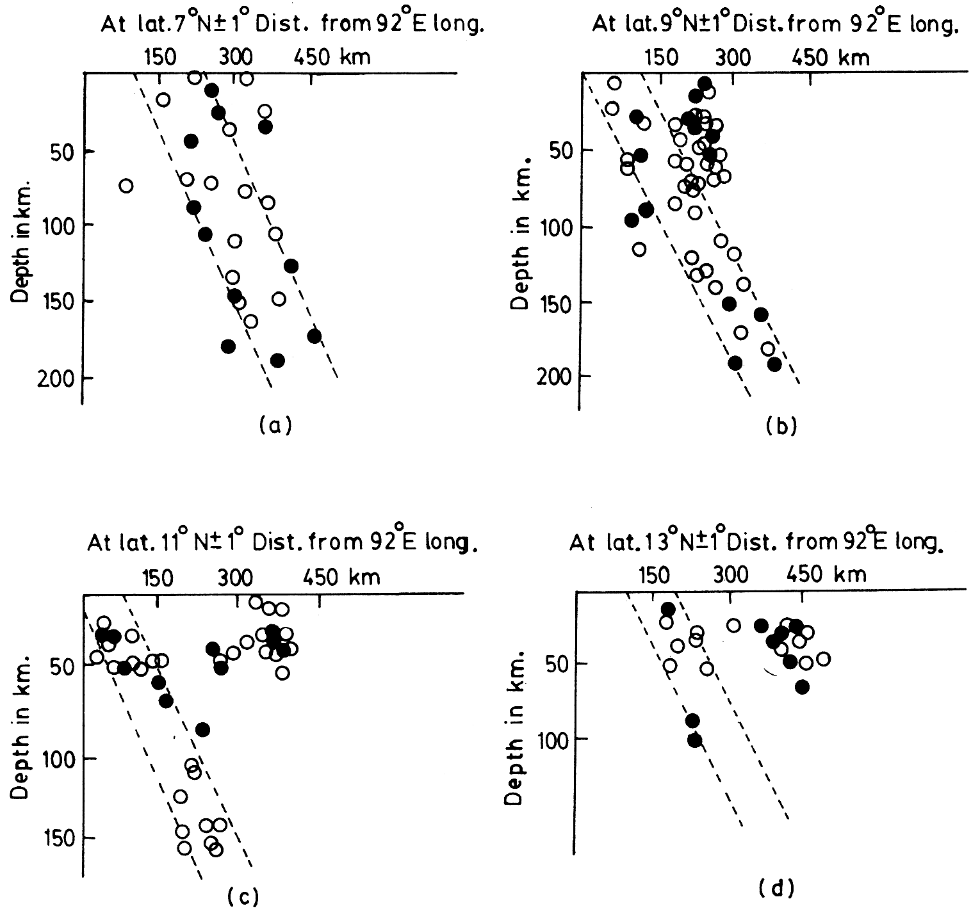

Figure 4. Depth-distance cross sections in the Andaman-Nicobar region (1964-1982). Open circles denote earthquakes up to magnitude 5 and solid circles greater than 5.

pose no consistency problems in *b*-values estimation as it follows very well the G-R relationship. But for the whole region (where *b*-value is obtained from body wave magnitudes) it should be clearly understood that (see Fig. 3) $\log_{10} N$ is 1 to 2 orders of magnitude larger for M_b as compared to M_L not because of differences of activity with time. As Aki's relation is more useful for events with any magnitude, data sets for these two depth ranges in the Andaman and Nicobar Islands have, in fact, been normalised per year (average) and per unit area (depth/area wise) although the average *b*-value for the considered period is shown in Table 1. If criticaly analysed, it could well be understood that there is no such variation in *b*-values depthwise (1.05 and 0.98) in the Andaman Islands region. This would imply that rate of stress accumulation and/or rate of energy release remains constant for a longer duration of time in the entire Andaman region. In contrast, a marked difference or change in *b*-value (depthwise) has been observed for the Nicobar Island region. A comparison in *b*-value variations is also made for the Circum-Pacific region (Table 3, Carter and Berg, 1981). It is clearly seen from this table that *b*- value is much lower in the entire Circum-Pacific region in comparison to the Andaman-Nicobar Island regions. Such lower *b* -values indicate that the Circum-Pacific region is much more active seismically than the Andaman-Nicobar region. In the Nicobar region, however, changes in *b*- values depth-wise would probably suggest that within the 33 km depth range ($b = 0.95$) earthquake activity is more pronounced with higher magnitudes whereas they are sporadic below 33 km depth range ($b = 1.42$). In otherwords, it would suggest that the recurrence interval for earthquakes with large magnitudes occurring below 33 km in the Nicobar Islands may be much larger than these occurring in the upper half. The changes in stress depthwise as reflected from *b*-values in the Nicobar Islands pose an interesting question. Why doesn't the b-value rise even after the release of a number of earthquakes during the period 1967- 1974? One possibility is that the first few shocks occur in areas where stress is still high. Increases in the *b*- value would not occur, then, until later in the sequence. Another possibility is that the stress might be accumulated outside the zone so that when the large earthquakes occur the stress is transmitted into the shallower depth range of Nicobar Island through stress diffusion (Anderson, 1975), thereby lowering *b*-value. Thus observations on the *b*- value vs. stress conditions reflect very well the seismicity level of a region.

4. Focal depth distribution of earthquakes

The spatial distribution of earthquakes beneath the trench-island arc system is the direct indication of the nature of seismic zone, underthrusting geometry and the kinematic process operating there. Thus four focal depth distance cross sections have been made across the structural lineaments of Andaman-Nicobar Island arc system to contribute to the understanding of the nature of seismic zone, their geometry and mode of subduction beneath this island arc. Seismic profiles are constructed eastward from longitude 92°E at the latitudes 7°N, 9°N, 11°N and 13°N respectively and are shown in Fig. 4. Locations of earthquakes which have been used in the preparation of seismicity map and focal depth studies were collected from IMD, ISC and USGS magnetic data file. The locations of these events were determined following the Jeffreys-Bullen earth model (1952). Available seismograms of Indian station network particularly those of the stations situated in north-east India and Port Blair were also consulted for this purpose and all the earthquake parameters, specially the location and focal depths were verified through the Hypo 71 program (revised, Lee and Lahr, 1972) using the J-B model. These seismic profiles across the subduction zone, however, pose a problem particularly about the wider seismic zone which is yet to be understood. Moreover the accurate determination of hypocentres is difficult in the region between the trench and island arc and minor systematic errors in focal parameters in some events can not be excluded in this region.

Seismic cross-sections along the latitudes 7°N and 9°N (Figs. 4a and 4b) clearly indicate the presence of a steeply inclined (eastward) deep riding seismic zone (depth ≅200 km) in this region. This implies high angle subduction of the Indian plate taking place against the Andaman-Nicobar Island arc. Presence of thicker seismic zone at lat. 7°N is yet to be explained. Fig. 4c shows a somewhat different picture. At latitude 11°N the presence of a steeply dipping seismic zone towards east, comparable to the one shown in the seismic cross section at latitude 7°N and 9°N (Fig. 4a and 4b), is found. But this profile also shows the presence of another cluster of shallow focus earthquakes away from the main inclined seismic zone. This shallow focus seismic zone is mainly related to the back arc activity i. e. the rifting of the central Andaman through where extension of the marginal Andaman Sea is currently taking place. This branching out of the seismic zone is also noticed indistinctly at latitude 9°N. Fig. 4d shows that clusters of earthquakes on eastern side of the seismic zone may possibly be related to the back arc activity while the cluster of earthquakes on the western side may directly be related to the underthrusting Indian plate beneath the island arc. The absence of deeper earthquakes in this zone is not yet clearly understood.

These seismic profiles imply that highly oblique steep subduction zone exists beneath the Andaman-Nicobar Island arc system. The process of evolution or development of such high angle subduction with back arc opening or extension can not be readily explained by a unique model. Chase (1978) suggested that when overriding plate above the trench is retreated with reference to the trench line, back arc extension might have evolved with steep subduction (Mariana type) and this is the case of the Andaman Sea. Another possibilty is that the age of subducting plate controls the mode of subduction (Molnar and Atwater, 1978). Because plates become heavier and cooler as they travel away from the spreading ridge, older plate probably sinks with greater speed and less coupling with landward plate, giving rise to Mariana type high angle subduction. The third possibility is that the mode of subduction depends on difference in the strength of coupling between the two plates at contact zone (Kanamori, 1977). Subduction starts with low angle thrusting of the Chilean type mode and as the process goes on, the coupling is gradually weaker and finally the Mariana type subduction evolves. Despite these possibilities, however, the problem is still unsolved because all these possibilities seem to contain some truth, and, therefore it is not clear if any of them is the only truth, exclusive of others.

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