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Earthquake slip vectors in the Himalayan thrust zone and their tectonic implications

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सार — हिमालय संघट्टन क्षेत्र के साथ होने वाली क्षेप की 39 घटनाओं के सर्पी सदिशों की तुलना, आरएम 2 और नूवेल 1 मॉडलों से व्युत्पन्न भारतीय यूरेशियन प्लेटों के मध्य वेग सदिशों के साथ की गई है। वेग सदिश से सर्पी सदिश के प्रेक्षित विचलनों को सरल शुद्धगतिक मॉडल के अनुसार प्रस्तुत किया गया है, जिसके अनुसार दक्षिण तिब्बत के पूर्वी और पश्चिमी खंड एक दूसरे से अलग होते हैं। मॉडल से यह अनुमान लगाया गया है कि यूरेशिया के संदर्भ में तिब्बत के पश्चिमी और पूर्वी खंड क्रमश: 76° पू० पर पश्चिम की ओर 3.6 से० मी०/वर्ष और 94° पू० पर पूर्व की ओर 2.6 से० मी०/वर्ष की दर से अग्रसर हो रहे है जिसके परिणामस्वरूप पूर्व-पश्चिम दिशा में विस्तार हुआ है जो कि 5.5 से० मी०/वर्ष की दर से 85° पू० की ओर प्रक्षिप्त है। यह मध्य तिब्बत क्षेत्र में लगभग 6.9×10^{-8} प्रति वर्ष की तनाव दर के अनुरूप था।

ABSTRACT. Slip vectors of thirty-nine thrust events occurring along the Himalayan collision zone have been compared with the velocity vectors between the Indian-Eurasian plates derived from the RM 2 and NUVEL 1 models. The observed deviations of the slip vector from the velocity vector have been interpreted in terms of a simple kinematic model according to which the eastern and western blocks of south Tibet are separating from each other. From the model it is estimated that the western and eastern blocks of Tibet are moving at the rate of 3.6 cm/year westwards at 76°E and 2.6 cm/year eastwards at 94°E with respect to Eurasia respectively, resulting in an east-west extension, projected to the trend at 85°E, at the rate of 5.5 cm/year. This would correspond to a strain rate of about 6.9×10^{-8}/year in central Tibetan region.

Key words—Slip vectors, Thrust zone, Tectonics, Extension, Strain rate.

1. Introduction

The continued convergence between the Indian and Eurasian continents appears to be the most probable cause of the observed deformation in central Asia (*e.g.*, Molnar and Tapponnier 1975). The deformation may be observed in the shortening along the thrust faults throughout the entire Himalayan front (Himalayan Frontal Thrust, Main Boundary Thrust, Main Central Thrust), the lateral displacement along the strike-slip faults, *viz.*, the Altyn Tagh and Kunlun faults in western and eastern Tibet, and the extension along normal faults in central Tibet (Molnar and Tapponnier 1975, Ni and Barazangi 1984, Tapponnier *et al.* 1986, Molnar and Deng 1984, Baranowski *et al.* 1984). Studies of earthquake mechanisms play a key role in corroborating the geologically obtained deformation data and discussing their tectonic implications. It appears that, through a detailed analysis of earthquake mechanism data, we may be able to understand the ongoing tectonic processes in the region. In this paper, thirty-nine thrust events occurring along the Himalayan thrust zones have been studied in an attempt to understand the possible relationship between their slip vectors and the velocity vectors derived from the global plate motion models of RM 2 (Minster and Jordon 1978) and NUVEL 1 (De Mets *et al.* 1990). From a comparison between the slip vector and the velocity vector along the arc, we derive a simple kinematic models which proposes that the eastern and western blocks of southern Tibet are separating from each other. The occurrence of normal and strike slip type of faulting in south Tibet has been discussed in the frame work of this model.

2. Data and analysis

From the published literature, thirty-nine thrust events occurring along the Himalayan thrust zones, of which the shallow dipping nodal planes dip more or less northerly, have been selected. This ensures the assumption that the selected events are associated with the process of underthrusting. Only the events having the nearly vertical nodal planes, to which the slip vectors are perpendicular, are well-contrained were selected. The list of the selected events is given in Table 1. The azimuth of the slip vector obtained from the focal mechanism solution for each event is also listed in this table.

We compare these slip vectors with the relative motion between the Indian and Eurasian plates. The rotation vectors used are from RM 2 (Minster and Jordan 1978) and NUVEL 1 (De Mets *et al.* 1990). The relative plate motion of the Indian plate with respect to the Eurasian plate has been calculated at each epicentral location using both the models above. Figs. 1 & 2 show the azimuths of the slip vector (dotted line) and the velocity vector (solid line) at each epicentral location for the NUVEL 1 and RM 2 models respectively. The azimuth of the velocity vector measured from the north and the magnitude of the velocity for the NUVEL 1 model are tabulated in Table 1.

3. Results

For a thrust event with a well-constrained mechanism solution occurring along the main thrust zone, the slip vector should, in general, correspond to the velocity

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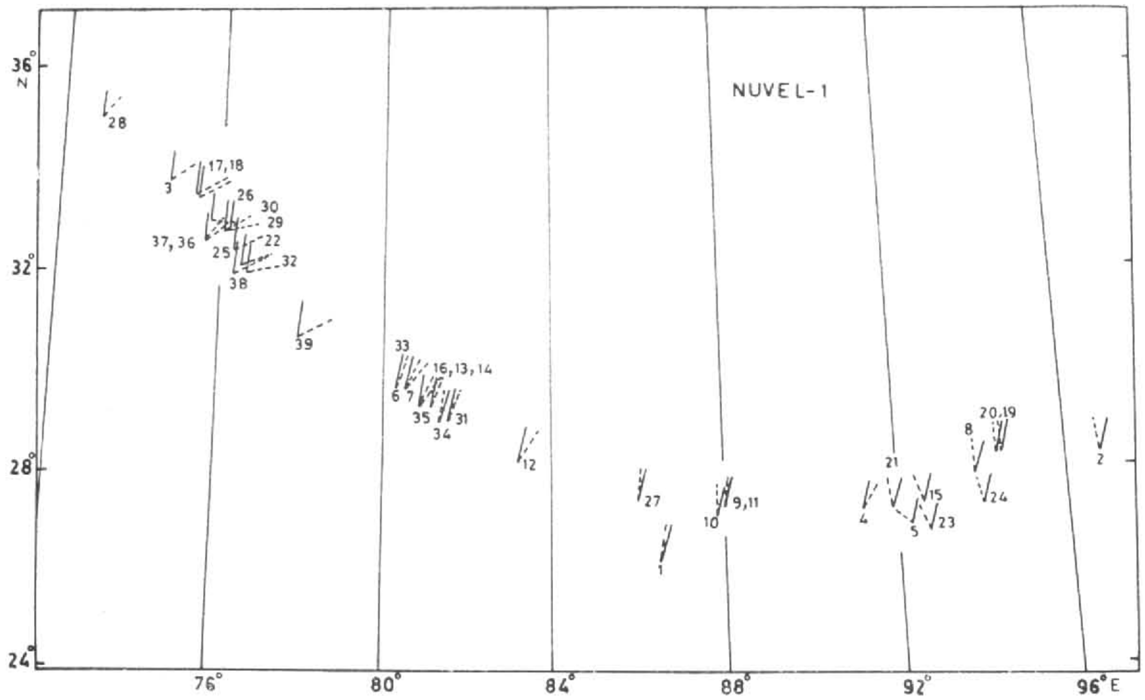

Fig. 1. Orientation of the slip vectors (dashed line) and the corresponding velocity vectors (solid line) for NUVEL 1 (De Mets *et al.* 1990). Numerals indicate the event number referred in Table 1

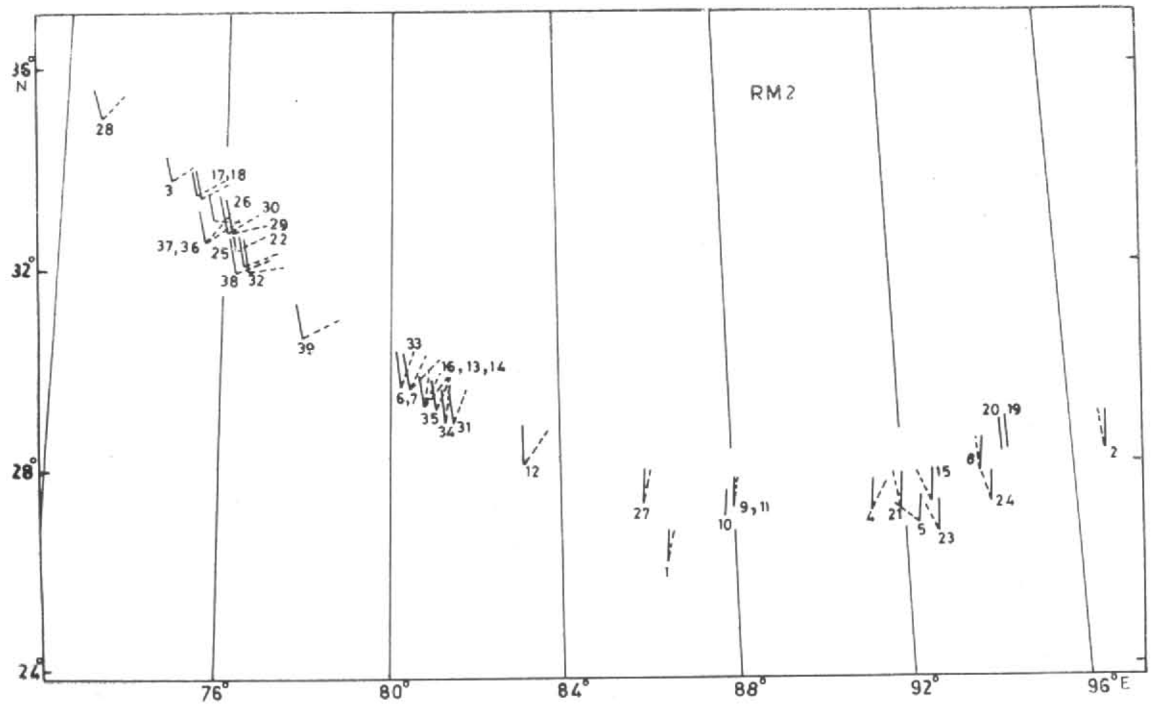

Fig. 2. Orientation of the slip vectors (dashed line) and the corresponding velocity (solid line) for (Minster and Jordan 1978). Numerals indicate the event number referred in Table 1

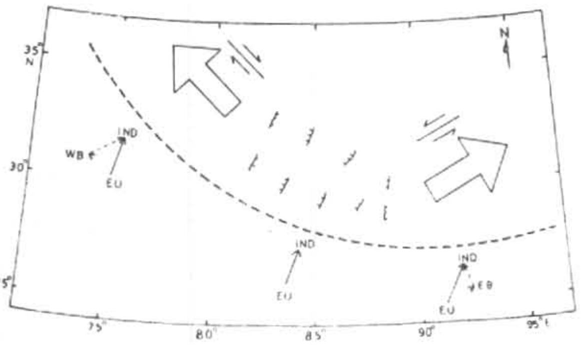

Fig. 3. Schematic model showing the east-west extension caused by the eastward and westward movement of eastern and western blocks respectively with respect to Eurasian plate

vector, provided that the rotation vector adequately describes the relative plate motion between the underthrusting and over riding plates. It is, therefore, possible that any systematic deviation between these two vectors may imply that the southern Tibetan area is not part of the Eurasian plate, if the uncertainties in the nodal plane orientation are within tolerable limits. For the slip vectors treated in this study, the uncertainty in slip vectors would be about 10-20 degrees. From Figs. 1 & 2, we may find that there exists a systematic deviation between the slip vector and the corresponding velocity vector calculated at the epicentre beyond the uncertainty in slip vectors. It may be noticed that the difference between the two vectors occurs on the eastern and western flanks of the Himalayan arc with an opposite sense. In other words, the majority of the slip vectors on the western flank show a clockwise rotation with respect to the velocity vectors, whereas those on the eastern flank show a counter-clockwise rotation. The change over from clockwise to counter-clockwise rotation takes place somewhere between the longitudes 84°-86°E for NUVEL 1 and 85°-88°E for RM 2. Around this location the slip vectors more or less coincide with the velocity vectors. From a comparison between Figs. 1 & 2, we may find that this deviation of the slip vectors from the velocity vectors is more symmetric for NUVEL 1 than for RM 2.

The observed deviations between the two vectors may be well explained by a simple kinematic model shown in Fig. 3. The vector diagram shown in this figure explains the counter-clockwise rotation of the slip vectors on the eastern flank of the arc if we assume an eastward movement of the eastern block (EB) along the arc with respect to the Eurasian plate. Similarly, the clockwise rotation of the slip vectors on the western flank of the arc may be attributed to the westward movement of the western block (WB) along the arc with respect to the Eurasian plate. This opposite sense of relative motion between the eastern and western blocks may in turn result in an east-west extension in central southern Tibet.

On the basis of this model, we calculated the velocity of the movement of the eastern and western blocks of Tibet with respect to the Eurasian plate for NUVEL 1. For simplicity, the curvature of the Himalayan arc as approximated by Seeber *et al.* (1981) has been adopted (Fig. 3) for estimating the arc trend at each epicentral location. In Fig. 3, EB, WB, EU and IND denote the eastern block, western block, Eurasian and Indian plates respectively. Solid and dashed arrows represent the velocity vector of the IND-EU motion and the slip vector of the thrust events respectively. Dotted arrows represent the relative motion between the WB/EB and the Eurasian plate. We assumed the motion between EB (or WB) and Eurasia is parallel to the arc trend. The numerical values designated by the letter a in Table 1 denote the relative motion of the western or eastern block with respect to Eurasia at each epicentre with the '+' sign indicating a westward motion and the '—' sign indicating an eastward motion. Fig. 4 shows a plot of a-value *versus* longitude. By a least square fitting, we obtained an expression of the form :

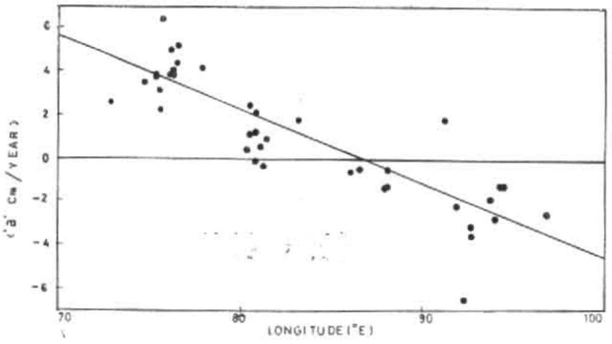

Fig. 4. Plot of a-values (cm/year) *versus* longitude (deg. E) for the events listed in Table 1. '+' or '—' signs of a represent the westward or eastward motion of the block respectively with respect to the Eurasian plate

$$a = 29.4 - 0.34 \times \text{Longitude (°E) (cm/year)} \quad (1)$$

From this relation, the motion of the western block was estimated to be 3.6 cm/year in the direction of N43° W at 76° E and that of the eastern block 2.6 cm/year in the direction of N83°E at 94° E. These velocity vectors are projected to the arc trend at 85°E at which the slip vectors more or less coincide with the velocity vectors. producing an extension of 5.5 cm/year; this would correspond to a strain rate of about 6.9×10^{-8}/year in central Tibetan region, if we divide the extension rate by the 800 km length of the extension zone shown in Fig. 3.

4. Discussion

Evidence for the east-west extension in the Tibetan plateau has been cited earlier by several investigators using the information on, (a) geological field studies of active faulting (Ni and York 1978, Tapponnier *et al.* 1982, Armijo *et al.* 1986), (b) landsat imagery (Molnar and Tapponnier 1978), and (c) fault plane solutions of earthquakes (Molnar and Chen 1983, Ni and York 1978). Tapponnier *et al.* (1986) using field studies of active faults in south Tibet, suggested that quaternary extension has been taking place at a rate of approximately 1 cm/year in a direction N100°E. Molnar and Tapponnier (1978) using landsat imagery data have concluded that north-south striking normal faulting appears to be a dominant mode of present crustal deformation within the Tibetan plateau; in contrast to large scale left lateral strike-slip faulting in northeast Tibet. Tapponnier *et al.* (1982) have also mapped several en

TABLE 1

Thrust events studied

S. No.	Date	Epicentre		Azim. of slip	Azim. of vel. vector (°E N)		*a*	*a*	Ref.
	D M Y	Lat. (°N)	Long. (°E)	(°E N)	RM 2	NUVEL 1	(cm / year)		
1	15-01-34	26.50	86.50	10	3.0	14.6	5.2	—0.4	SG
2	15-08-50	28.33	96.76	—9	4.6	17.4	5.5	—2.5	MT
3	02-09-63	33.90	74.70	55	344.9	5.2	4.5	3.5	C
4	18-02-64	27.40	91.18	32	3.4	15.8	5.4	1.8	C
5	01-09-64	27.12	92.26	—46	3.9	16.2	5.4	—6.4	C
6	26-09-64	29.96	80.46	24	353.7	10.5	4.9	1.1	C
7	26-09-64	29.96	80.46	40	353.7	10.5	4.9	2.4	MT
8	21-10-64	28.04	93.75	—3	3.7	16.4	5.4	—1.8	F
9	12-01-65	27.60	88.00	9	2.6	14.6	5.2	—0.5	R
10	12-01-65	27.40	87.84	0	2.7	14.6	5.2	—1.3	ME
11	12-01-65	27.60	88.00	1	2.6	14.6	5.2	—1.2	C
12	01-06-65	28.50	83.20	33	356.4	12.4	5.0	1.8	R
13	27-06-66	29.62	80.83	26	354.3	10.8	4.9	1.3	C1
14	27-06-66	29.62	80.83	36	354.3	10.8	4.9	2.1	MT
15	26-09-66	27.49	92.61	—17	3.7	16.2	5.4	—3.0	C
16	16-12-66	29.62	80.79	10	354.2	10.8	4.9	—0.1	ME
17	20-02-67	33.70	75.30	59	345.6	5.6	4.6	3.7	C
18	20-02-67	33.60	75.40	60	345.8	5.7	4.6	3.8	T
19	11-03-67	28.40	94.40	3	3.7	16.5	5.5	—1.3	RE
20	14-03-67	28.40	94.29	3	3.6	16.5	5.5	—1.3	MT
21	15-09-67	27.42	91.86	—7	3.5	16.0	5.4	—2.1	C
22	05-11-68	32.30	76.50	68	348.4	7.2	4.6	4.4	CE
23	30-06-69	26.90	92.70	—22	4.2	16.5	5.4	—3.5	TS
24	19-02-70	27.40	93.96	—13	4.2	16.7	5.5	—2.7	ME
25	25-02-71	32.60	76.30	60	347.8	6.9	4.6	3.8	DE
26	16-01-73	33.20	75.70	90	346.6	6.2	4.6	6.4	VE
27	24-03-74	27.66	86.00	7	2.6	13.9	5.1	—0.6	MT
28	28-12-74	35.10	72.90	38	341.6	3.5	4.4	2.6	P
29	11-12-75	33.00	76.17	76	347.2	6.5	4.6	4.9	DE
30	01-01-76	32.97	76.12	60	347.2	6.5	4.6	3.8	DE
31	10-05-76	29.33	81.46	22	354.9	11.3	4.9	0.9	BD
32	14-06-78	32.24	76.61	78	348.5	7.3	4.6	5.2	DE
33	20-05-79	30.03	80.31	15	353.5	10.4	4.9	0.4	CMT
34	29-07-80	29.33	81.26	8	354.8	11.2	4.9	—0.3	CMT
35	29-07-80	29.60	81.09	18	354.4	11.0	4.9	0.6	CMT
36	23-08-80	32.84	75.56	50	346.9	6.4	4.6	3.2	CMT
37	23-08-80	32.82	75.60	36	347.0	6.4	4.6	2.3	CMT
38	26-04-86	32.09	76.31	63	348.5	7.3	4.6	4.0	CMT
39	16-07-86	30.94	77.88	62	351.0	8.8	4.7	4.1	CMT

SG—Singh and Gupta 1980, MT—Molnar and Tapponnier 1978, C—Chandra 1978, F—Fitch 1970, R—Rastogi 1974, ME—Molnar *et al.* 1973, C1—Chandra 1971, T—Tandon 1972, RE—Rastogi *et al.* 1973, CE—Chaudhury *et al.* 1974, TS—Tandon and Srivastava 1975, DE—Dasgupta *et al.* 1982, VE—Verma *et al.* 1977, P—Pennington 1979, BD—Biswas and Dasgupta 1986, CMT—Harvard CMT solution.

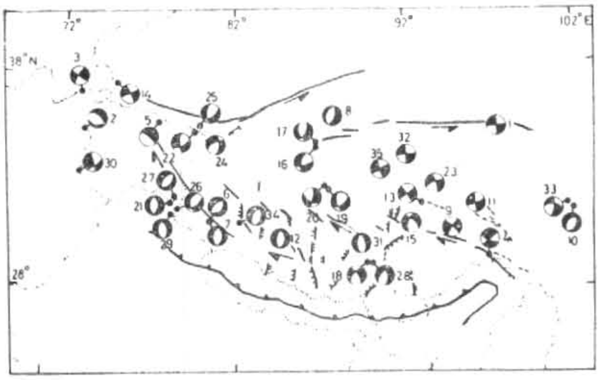

Fig. 5. Map showing the distribution of normal/strike slip type of mechanisms for earthquakes occurring in Tibetan plateau. Shaded and white portions indicate areas of compression and dilatation of the mechanism diagram (lower focal hemisphere) respectively. Numerals indicate the event number referred in Table 2. Active faults are taken from Armijo *et al.* (1986)

echelon normal/right-lateral strike-slip faults west of about 80°E which appear to be a continuation of the active Karakorum fault. We plotted the major active faults from these studies in Fig. 5.

Using synthetic waveform modelling. Molnar and Chen (1983) have placed constraints on the focal depths and the nodal planes for sixteen crustal earthquakes occurring beneath the Tibetan plateau. They have found that all the solutions show a combination of normal and strike-slip faulting with the *T*-axes oriented approximately east-west, suggesting a predominance of east-west extensional tectonics. The mechanism solutions of earthquakes showing normal and strike-slip faulting in Himalaya and Tibetan plateau are shown in Fig. 5. The source parameters together with the source of reference for each event are listed in Table 2.

We can see that the events show a predominantly strike-slip component in the eastern and western part in contrast to the predominance of normal faulting in the central portion of south Tibet. Furthermore, the strike-slip mechanisms in the east show a left lateral motion on a NE-SW nodal plane (No. 9, 11, 13, 15, 23) and those in the west show a right-lateral motion on a NW-SE nodal plane (No. 3, 14, 22). However, in the eastern flank of southern Tibet (92-95°E) there are some active faults striking NW-SE, with a right-lateral sense of motion (Fig. 5, Tapponnier *et al.* 1986). The fault plane solutions of events 9 and 13 are consistent with this right-lateral motion, if we take a NW-SE trending nodal plane as a fault plane. This seems to contradict the model shown in Fig. 3. However, note that the model in Fig. 3 is too simple; there would possibly be internal deformation within EB. It is also known that some conjugate faults are sometimes activated associated with the displacements in the strike-slip faults. If the right-lateral motion on the NW-SE trending faults is true in southeastern Tibet, we believe that this represents such a complex deformation. Therefore, we feel that the spatial distribution of the active faults and the fault plane solutions in southern Tibet are generally consistent with the model in Fig. 3.

Molnar and Chen (1983), using seismic moment release estimated the strain rate in Tibet as 4.4×10^{-9}/year. For a region 1000 km wide in an east-west direction, this corresponds to 4.4 mm/year extension between the eastern and western Tibets. Field studies of active faulting in south Tibet by Tapponnier *et al.* (1986) have indicated that quaternary extension has been taking place at a rate of about 1 cm/year. The extension rate estimated in this study is by factor five larger than those estimated geologically and by one order from the seismic moment release. The relatively lower estimates of extension based on geological field studies may be due to the fact that these estimates might not have taken into account all the active faults in this region. Similarly, the estimates of extension based on the seismic moment release apparently may not account for all the moment release in central south Tibet because of the limited time of observation, thus resulting in underestimation of the extension rates. Part of the extension may also be taken up by the aseismic ductile deformation of the crust in southern Tibet. On the contrary, the estimates of extension rate, obtained kinematically in this study may be too simple, since the model does not take into account the deformations within the eastern and western Tibets.

As regards a possible explanation for the east-west extension in southern Tibet, there are several schools of thought. The oblique subduction of the Indian plate beneath the Eurasian plate along the Himalayan arc may possibly drag the eastern and western blocks of southern Tibet to be decoupled from Asia and may have caused the east-west extension. Fitch (1972) had proposed a model for oblique convergence between plates of lithosphere in which at least a fraction of the slip parallel to the plate margin results in a transcurrent movement on a nearly vertical fault located on the continental side of a zone of weakness. Significant contribution for the observed east-west extension in Tibet may also arise from the gravitational effect of the thicker crust in the Himalayas and Tibet, which may result in material flow in an east-west direction (Froidevaux and Richard 1987).

TABLE 2

Normal/strike slip events in southern Tibet

S. No.	Date	Epicentre		Nodal plane 1		Nodal plane 2		Ref.
	D M Y	(°N)	(°E)	Strike	Dip	Strike	Dip	
				(E deg	N)	(E deg	N)	
1	19-04-63	35.53	96.44	182	88	272	82	TM
2	29-01-65	35.6	73.6	72	32	309	71	C
3	02-02-65	37.5	73.4	115	84	206	81	C
4	15-06-65	29.6	95.6	131	70	41	90	C
5	22-06-65	36.2	77.6	129	3	309	87	C
6	06-03-66	31.16	80.6	225	55	45	35	C
7	06-03-66	31.49	80.5	0	45	180	45	MC
8	14-10-66	36.45	87.43	25	66	205	24	MC
9	15-08-67	31.05	93.56	313	78	221	80	NY
10	30-08-67	31.57	100.31	30	40	227	51	TM
11	03-04-71	32.26	95.06	170	80	80	90	TM
12	03-05-71	30.79	84.33	190	58	10	32	MC
13	22-05-71	32.39	92.12	58	90	328	87	MC
14	12-01-72	37.7	75.1	246	90	336	75	C
15	22-07-72	31.38	91.41	212	65	309	75	MC
16	14-07-73	35.18	86.48	190	60	81	60	MC
17	14-07-73	35.26	86.60	37	68	156	40	MC
18	01-08-73	29.59	89.17	220	60	323	69	MC
19	16-08-73	33.24	86.84	160	55	55	70	MC
20	08-09-73	33.29	86.82	118	60	18	74	MC
21	19-01-75	32.39	78.5	0	50	180	40	MC
22	28-04-75	35.82	79.92	169	62	63	63	MC
23	05-05-75	33.09	92.92	250	78	343	76	MC
24	19-05-75	35.16	80.8	248	66	4	46	MC
25	04-06-75	35.87	79.85	180	62	52	41	MC
26	19-07-75	31.95	78.59	180	50	47	51	MC
27	29-07-75	32.57	78.49	210	55	30	35	MC
28	14-09-76	29.81	89.57	215	52	2	43	MC
29	29-09-76	31.83	78.4	158	40	350	50	BD
30	14-02-77	33.6	73.3	150	90	60	45	SA
31	22-02-80	30.55	88.65	185	48	339	44	NB
32	09-06-81	34.78	91.71	177	90	267	90	DW
33	15-06-82	31.66	99.7	286	71	20	78	DFG
34	23-01-82	31.69	82.25	203	67	23	23	USG
35	05-11-83	33.95	90.05	160	83	69	83	DFW

TM—Tapponnier and Molnar 1977, C—Chandra 1978, MC—Molnar and Chen 1983, NY—Ni and York 1978, BD—Biswas and Dasgupta 1986, SA—Seeber and Armbruster 1979, NB—Ni and Barazangi 1984, DW—Dziewonski and Woodhouse 1983, DFG—Dziewonski *et al.* 1983, USG—USGS solution, DFW—Dziewonski *et al.* 1984.

5. Conclusions

Comparison of the slip vector of thrust events occurring along the Himalayan thrust zone with the corresponding velocity vectors of the Indian-Eurasian relative motions shows systematic deviations between the two vectors. The majority of the slip vectors on the western flank show a clockwise rotation with respect to the velocity vectors, whereas those on the eastern flank show a counter-clockwise rotation.

To explain the deviation, a simple schematic extension model has been proposed incorporating the relative motions of the eastern and western blocks of the Tibetan plateau with respect to Eurasia. The relative motions of the eastern and western blocks of south Tibet with respect to Eurasia have been estimated at each epicentral location along the arc from the deviation of the slip vector from the velocity vector of NUVEL 1. From a least square fitting of the data, the motions of the western and the eastern blocks are estimated to be 3.6 cm/year westwards at 76°E and 2.6 cm/year eastwards at 94°E respectively with respect to Eurasia, implying an extension of 5.5 cm/year in central Tibet in a direction parallel to the trend at 85°E. This would suggest that the strain rate in central south Tibet is of the order of 6.9×10^{-8}/year in an east-west direction. The spatial distribution of normal and strike-slip faulting in Tibetan plateau as evidenced by fault plane solutions and some of the known seismotectonic features of the region is consistent with the kinematic model proposed in this study.

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