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GEOPHYSICAL IMPLICATIONS FROM RELOCATIONS OF TIBETAN EARTHQUAKES; HOT LITHOSPHERE

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Abstract. ISC locations for earthquakes beneath Tibet indicate a random distribution of events down to a depth of about 50 km. This distribution would be expected from a relatively cool crust which would allow the seismo-genic zone to extend to such depths. A detailed investigation of the Tibetan earthquakes, with magnitude greater than 5.5 from 1964 to 1986, yields a distinctly different picture. Waveform modeling of depth phases indicates that only a few events from this population is actually deeper than 25 km. These few events occurred near the edges of the Plateau where active subduction is occurring as suggested by the thrust-like nature of their mechanisms. The events, averaging the entire population, occurred earlier than indicated by the ISC by about 3 seconds which leads to about a 1.5% and 0.5% over estimation of P_n and S_n velocities respectively applying ISC tables and standard flat-layered models. A more serious error occurs if the P_n and S_n velocities are determined by correcting for source depth but assuming the ISC origin times.

Data, Analysis and Results

Short period and long period seismograms from about 60 significant Tibetan earthquakes are examined in this study. The long period body waveforms were used to estimate depths by applying waveform modeling techniques. Travel time determinations from the short period data were used in a new relocation scheme to relocate events with special emphasis on the origin times. Shallower locations corresponds to earlier origin times which tends to increase travel times and reduce apparent velocities.

The events studied are listed in Table 1. Included in this table are the ISC determinations of depth, location and origin times of these events along with new estimates obtained from this investigation. The main objective of this report is to document these results and discuss their significance.

Errors in depth determinations using travel times become serious when no local stations are available, which is the case in Tibet. Essentially, there is a complete trade-off between origin time and depth. This difficulty can be circumvented by determining the depths independently by applying waveform modeling of the P-waveforms [Langston and Helmberger 1975]. This technique models the interference between direct P and free surface reflections to fix the epicentral depth. The source depth will be 10% deeper if the crust velocity is 10% faster.

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Many of the P-waveforms from Tibetan events have been modeled previously by a number of authors as indicated in the Table. These solutions have been checked by

Table 1. Relocation of Tibetan Earthquakes

Date	Origin Time		ΔT	Location		D	Depth		N	ref
MoDaYr	h m	sec	(sec)	(°N,	°E)	(km)	relc	ISC		
031664	0105	13.5±1.2	-6.3	37.11	95.60	20.1	10	50	21	E
092664	0046	-3.1±1.3	-5.7	29.91	80.55	10.6	18	50	32	AE
102164	2309	15.8±1.3	-3.2	28.22	93.87	10.6	15	37	32	A
011265	1332	22.1±1.1	-2.0	27.41	87.85	1.8	15	23	27	A
020566	1512	27.2±1.0	-5.7	26.29	103.20	8.3	4	42	39	C
021366	1044	36.0±1.2	-2.0	26.27	103.25	10.6	4	6	32	C
030666	0210	52.1±0.8	+0.1	31.50	80.53	2.2	11	5	33	
030666	0215	49.8±1.1	-7.4	31.48	80.50	10.0	8	50	37	D
062766	1041	04.2±1.2	-3.9	29.70	80.89	10.4	15	33	42	A
081566	0215	29.9±1.1	+1.9	28.70	78.91	4.5	25	5	31	
092666	0510	54.5±1.1	-1.7	27.53	92.73	12.9	17	20	34	
092866	1400	18.5±1.3	-2.5	27.55	100.10	2.5	10	12	42	C
101466	0104	40.0±1.2	-2.9	36.50	87.46	6.3	8	14	32	D
121666	2052	14.1±1.5	-2.2	29.66	80.84	6.1	12	19	40	A
031467	0658	02.8±1.5	-1.6	28.57	94.37	19.0	15	20	36	A
081567	0921	-2.6±0.9	-5.9	31.23	93.56	17.0	8	36	25	C
083067	0422	01.8±1.2	-3.2	31.71	100.24	11.7	10	24	35	CH
083067	1108	44.8±1.4	-6.2	31.73	100.28	18.1	8	35	28	CH
021970	0710	00.2±1.4	-1.3	27.47	94.02	9.7	10	12	19	
022470	0207	31.5±1.4	-4.5	30.66	103.02	6.2	7	24	27	E
032471	1354	15.2±1.2	-3.2	35.46	98.03	0.9	7	13	40	E
040371	0449	-2.2±1.4	-5.3	32.19	95.08	8.9	8	27	40	
040371	0450	39.8±1.4	-5.6	32.10	95.10	8.9	8	33	25	C
052271	2003	27.3±1.3	-4.6	32.42	92.11	6.7	8	29	43	CD
083072	1514	05.0±1.3	-2.5	36.64	96.35	1.3	15	17	31	E
083072	1847	38.6±1.2	-1.7	36.71	96.46	18.9	19	16	30	E
090372	1648	24.4±0.9	-5.1	36.06	73.31	13.6	12	45	37	AC
020673	1037	06.1±1.5	-0.9	31.38	100.54	6.7	10	5	37	H
020773	1606	20.7±1.3	-5.1	31.58	100.28	10.2	8	35	35	C
071473	0451	16.1±1.5	-3.9	35.25	86.41	10.0	6	22	48	CD
071473	1339	24.1±0.7	-5.3	35.30	86.51	10.7	7	29	18	CD
011575	1134	37.0±1.2	-4.0	29.46	101.78	5.3	10	29	41	C
011975	0801	57.6±1.4	-0.4	32.39	78.58	7.5	9	1	36	D
081676	1406	44.5±1.4	-0.5	32.80	104.09	3.8	12	9	35	F
082176	2149	49.1±1.1	-2.9	32.58	104.29	1.2	5	15	17	F
082376	0330	02.9±1.2	-3.1	32.55	104.24	8.8	8	17	20	F
111877	0520	06.7±1.1	-3.4	32.75	88.44	12.4	10	24	22	CE
032979	0707	15.3±1.3	-6.7	32.55	97.28	12.9	10	45	32	CE
021380	2209	32.3±1.2	+1.5	36.61	76.85	15.1	90	74	36	B
022280	0302	42.8±0.7	-2.4	30.65	88.61	11.0	10	14	34	EFG
060180	0619	-5.2±1.1	-6.3	39.06	95.63	16.5	12	50	26	E
062480	0735	44.7±1.2	+0.0	33.02	88.46	9.2	11	3	25	E
072980	1458	39.4±1.0	-2.2	29.64	81.08	7.5	15	23	39	EF
082380	2136	48.9±1.5	-0.1	33.07	75.69	13.0	14	3	27	E
082380	2150	-0.5±2.0	-1.5	32.89	75.83	3.2	13	12	28	E
100780	0932	03.0±1.3	-5.7	35.63	82.21	6.5	4	32	29	E
111980	1900	45.5±0.9	+0.5	27.47	88.80	7.9	14	1	45	F
012381	2113	46.5±1.2	-5.5	30.99	101.14	11.4	8	34	22	H
060981	2208	17.6±1.3	-1.0	34.65	91.34	21.1	10	10	29	CE
012382	1737	25.8±1.2	-3.4	31.74	82.27	6.6	10	25	33	
061582	2324	26.5±1.2	-2.3	31.91	99.92	7.1	7	10	34	CE
021383	0140	08.2±1.9	-0.9	40.05	75.17	9.0	5	0	29	C
052085	1511	35.6±0.5	-3.3	35.62	87.28	9.9	8	19	13	E
042686	0735	12.6±1.3	-3.6	32.23	76.39	11.8	13	33	28	E
062086	1712	43.5±1.2	-3.7	31.23	86.79	3.0	15	33	27	CE
070686	1924	20.9±1.2	-2.2	34.55	80.15	12.3	5	9	28	E
071686	2203	07.7±1.6	+0.7	31.10	78.08	8.8	13	4	25	
082086	2123	51.2±1.2	-2.8	34.65	91.49	17.1	11	25	24	E
082686	0943	-1.2±1.4	-1.7	37.83	101.55	10.7	7	8	29	

A Baranowski et al.,1984 E Molnar & Lyon-Caen, 1989
B Fan & Ni, 1989 F Ni & Barazangi, 1984
C Holt & Wallace, 1990 G Zhao et al., 1991
D Molnar & Chen, 1983 H Zhou et al., 1983

adding station coverage and, in general, found to be satisfactory. New depth estimates from modeling these events assuming the crustal model given in Zhao, Helmberger and Harkrider [1991], model TIP, are listed in Table 1.

We used the P wave travel times for relocations. These usually agreed with the ISC reports except in a few cases. More than 30 travel time picks distributed in azimuth are available for most events, thus providing excellent coverage. The station coverage is indicated in the Table 1. The relocation procedure used is simple iteration scheme based on the definition of the ray parameter p, namely,

$$p= dT/dR \quad \text{or} \quad dR= dT/p \qquad (1)$$

where dT is a small change in travel time associated with a small change in location. We start with the origin time and location given by ISC. We define

$$dT= (T_{obs}- T_0)- T_c \qquad (2)$$

where T_{obs} is the observed time, T_0 is the origin time and T_c is the theoretical travel time based on an earth model. We assume TIP is the appropriate model at source region along with elevation correction and the model JB at the receiver stations. Dziewonski and Anderson's [1983] Station corrections were applied. By assuming that the dT's are from a Gaussian distribution, we form the expectation estimate

$$\delta T= \frac{1}{n}\sum_{i=1}^{i=n} dT_i. \qquad (3)$$

and obtain a new origin time $T_{0new}= T_{0old}+ \delta T$. From equations (2) and (3), we can see that δT based on this new origin time is zero.

Then we use the new dT assuming T_{0new} given in Equation (2) to determine the mislocation dR from equation (1). We find the estimated mislocations in the North dx and East directions dy, namely,

$$dx= -\frac{1}{n}\sum_{i=0}^{i=n} dR_i\cos\Phi_i \qquad dy= -\frac{1}{n}\sum_{i=0}^{i=n} dR_i\sin\Phi_i \qquad (4)$$

assuming Gaussian distributions of the two direction mislocations, where Φ_i is the azimuth of the source to the station (i). The new location of the earthquake is given by latitudes θ_{new} and longitude ϕ_{new}:

$$\theta_{new}= \theta_{old}+ dx/ R_E \qquad \phi_{new}= \phi_{old}+dy/ (R_E\cos\theta_{old}). \qquad (5)$$

Next we use the new origin time and new location as initial values, we use equations (3) and (5) to calculate the new origin time and location, until some criteria is met. The criteria we used here is that the difference of the standard errors of the two iterations is smaller than 0.01 seconds. In this inversion we assume that the source depth is known, but this assumption is not required by the method. The method converges fast, normally under 5 iterations and the final results is not dependent on the initial input. Since changing the origin time trade-offs with T_c, the ISC locations are not effected much by changing the source depths.

The relocation scheme introduced here is different from the standard ones, see Aki and Richards [1980]. In stead of using independent variables of origin time and two (fixed depth) or three location parameters, we assume the origin time only in this scheme. The calculation of matrix inverse is avoided.

After relocation, if the travel time residual of certain station is greater than three seconds, we consult the record again. If there is no problem with the pick, we use it; if the pick is not certain, buried in the noise, we may throw it away depending on the confidence of the pick, and event size, and all other station conditions. We reject data that have a residual more than 5 seconds, even though the onset is sharp. For example, UME and SEO produce more than 10 second residuals for some of the large earthquakes, and perhaps were caused by improper clock corrections.

We summerize our results in Table 1. In the table, " relc " means relocation, " D " is the distance between the relocated location and ISC location, " ΔT " is the relocated origin time difference from that of ISC. We also give number of stations used under " N ". Under " ref ", we give the references. The standard error of the origin time due to the inversion are also given in Table 1.

Figure 1 displays the contrast between the ISC depth determinations versus the new estimates for more than 90 per cent of the events with magnitudes greater than 5.5 that have occurred since 1964. The results are dramatic where all the events occurring beneath the interior of Tibet

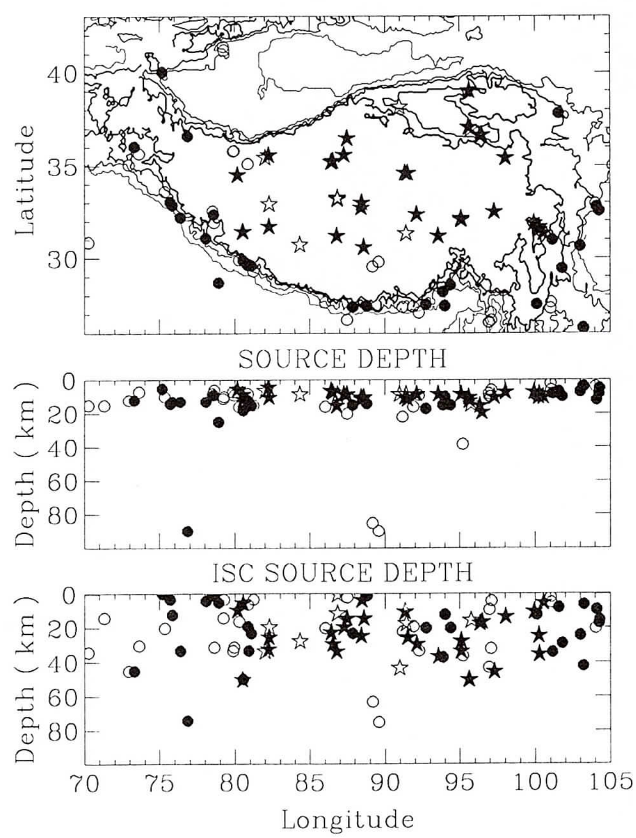

Fig. 1. The source depths before and after relocation. The top plot shows the locations of the earthquakes whose depths are plotted below. The dots are the earthquakes on the Tibetan boundary, the stars are inside Tibet. The middle plot shows the source depth distribution after relocation and the bottom plot shows ISC depths. The solid symbols indicate the events that we relocated in this study.

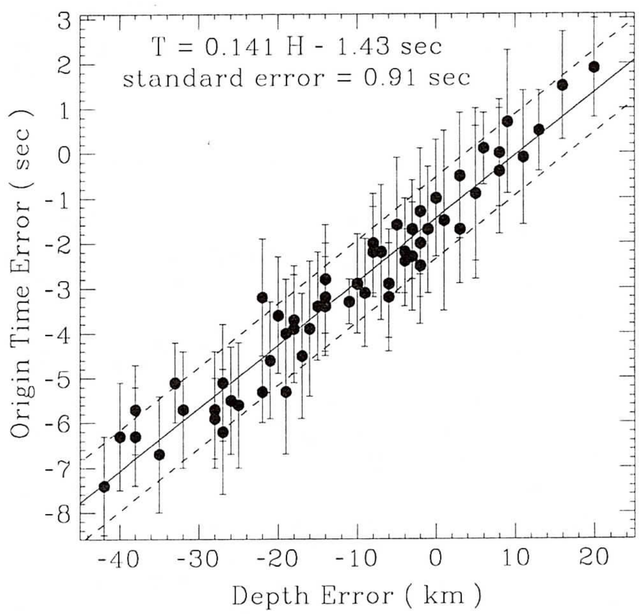

Fig. 2. Origin time error verses depth error respects to the ISC reports. The vertical lines show the error bars.

become shallow events while the events along the frontal thrust zone become deeper. This implies a warm lower crust beneath Tibet similar to other tectonic regions.

The crustal temperature increases with depth is generally accepted as the reason for the shallow nature of seismicity. This gradient is strongly influenced by radiogenic material in the continental crust. Thus with the greatly thickened Tibetan crust, roughly a factor of two, we would expect the temperature to be elevated by 300° compared to normal stable regions, see Zhao et al. [1991]. Such a high temperature would be expected to reduce the mantle velocity by about five per cent which is observed when using the proper origin times as discussed later.

The mislocations are not very significant, the greatest is 21.1 km. The origin time corrections are more serious. Of the 59 earthquakes, 54 earthquakes occurred earlier than reported by ISC. The average of all earthquakes is -3.1 seconds, or these earthquakes have occurred 3.1 seconds earlier than reported by ISC. The worst case is -7.4 seconds for the second March 6, 1966 earthquake. Eleven of the events have a residual greater than 5.5 seconds.

Figure 2 shows the depth error verses origin time error, with respect to those of ISC. The new points should show a linear trend based on the assumed earth model. The least square fit of the data yields:

$$T= 0.141H- 1.43 \qquad (6)$$

where T, origin time error in seconds, H depth mislocation in km is equal to relocated source depth minus ISC source depth. The standard error is 0.55 seconds if we assume that the origin times do not have errors and the standard error is 0.91 seconds if the error bars are included. The least square fitting method that includes error bars assumes that the probability distribution on the bars is constant, the non-information probability density. The coefficient of H, 0.141, is dependent on the input model TIP, 6.16 to 6.55 km s^{-1} of source layer, and the average ray parameter. The offset of -1.43 seconds comes from the differences of earth model, the station correction and topographic correction relative to ISC assumption.

Discussion

Barazangi and Ni [1982], and Ni and Barazangi [1983] used P_n- and S_n- waves crossing the Tibetan Plateau, and obtained velocities of 8.42km s^{-1} for P_n, and 4.73km s^{-1} for S_n. Holt and Wallace [1990] inverted the P_{nl} waveform data and concluded that the P_n velocity is 8.24 km s^{-1} beneath the Tibet region. Zhao et al. [1991] reported that the P_n velocity beneath the Tibetan Plateau is 8.3 km s^{-1}, and that the S_n velocity is 4.6 km s^{-1} by modeling SS and S waveforms. Zhao et al. [1991] did not use the absolute travel time in developing the velocity model TIP, but rather the differential travel times of SS–S, thus their results on the upper mantle velocities are not effected by the accuracy of the origin times. Using P_{nl} waveforms and the travel times of P_n and S_n phase may introduce two per cent higher lid velocity bias due to the non-planar characteristics of the Moho boundary beneath the Tibetan Plateau as given by Zhao and Helmberger [manuscript in preparation].

Models based on absolute travel times obviously depend on the origin time. For example, Holt and Wallace [1990] used 24 events from population given in Table 1. They assumed these events are shallow with depths similar to the relocated depths given in Table 1, and applied the ISC origin times with corrections of the source depth, dipping Moho and 70 km crust. If they did not correct the origin times, their P_n travel times would be 3.6 seconds too short relative to the results presented in Table 1 on average. Although they over corrected the effects of the velocity structure of source region, two seconds, (they assume a JB velocity distribution beneath the crust of the Tibetan Plateau), their P_n velocity, 8.24 km s^{-1}, is reasonable.

The origin time effects on the P_n and S_n results from the regional phases are slightly less dramatic, if both the source depths and origin times of ISC are used. This is because the deeper source depth of ISC compensates its later origin time. The effects of origin time errors and depth errors on the travel times of P_n and S_n are given by

$$\Delta T_{P_n} = -\,0.034H + 1.43 \qquad \Delta T_{S_n} = 0.044H + 1.43 \qquad (7)$$

assuming that the compressional velocity 6.2 km s^{-1}, the shear velocity 3.5 km s^{-1} for the crust and velocities for the mantle are 8.3 and 4.6 km s^{-1} respectively. Averaging over all the relocated earthquakes, yields $\Delta T_{Pn} = +\,1.8$ seconds and $\Delta T_{Sn} = +\,0.95$ seconds.

The travel time of P_n phase recorded at a station 10 degrees away from the source is about 140 seconds. From Equation (7), the P_n travel time is 1.8 seconds longer than that predicted by using ISC origin time and source depth, averaging over all the relocated earthquakes. Considering this travel time difference, we get a P_n velocity of 8.43 km s^{-1} by using the P_n travel time predicted by using ISC source depth and origin time if the real P_n velocity is 8.30 km s^{-1}. This velocity difference almost covers the possible models proposed for the Tibet region discussed earlier.

Table 2.

Data	Time	Station	Distance	ΔD	ΔT_{syn}	ΔT_{obs}	δT
08 15 67	0921	SHL	649	19.2	5.5	5.9	0.4
08 30 67	1108	NDI	2242	-2.1	-0.6	6.2	6.8
08 30 67	1108	LAH	2456	-4.9	-1.4	6.2	7.6
08 30 72	1514	NDI	1995	-0.4	-0.1	2.5	2.6
02 07 73	1606	NDI	2241	-4.4	-1.3	5.1	6.4
02 07 73	1606	NIL	2540	-6.6	-1.9	5.1	7.0
06 15 82	2324	NDI	2209	0.4	0.1	2.3	2.2

Following the above procedure, we get a S_n velocity of 4.62 km s^{-1} by using the travel time predicted by using ISC source depth and origin time if the real S_n velocity is 4.60 km s^{-1}. Thus the origin time and source depth given by ISC do not make very much difference to the S_n velocity if only S_n travel times are used. In short the travel time errors introduced by the ISC origin times and source depths lead to about 1.5% over-estimate of the P_n velocity and about 0.5% over-estimated of the S_n velocity.

The ISC location of the earthquakes are not badly mislocated. However this mislocation may introduce more than 5 seconds to regional Love wave travel times, since the group velocity of the maximum amplitude of Love waves is about 3.5 km/sec. Thus, this small mislocation can lead to a bias in the velocity model. For example, suppose we consider the events discussed by Zhao et al. [1991], see Table 2. In this table, ΔD is the distance between the old and new location in kms at a number of stations surrounding Tibet. Positive values mean that the new distances are larger, ΔT_{syn} is the synthetic travel time correction caused by the distance change assuming a 3.5 km/sec group velocity. ΔT_{obs} is the observed travel time change due to the change in origin time, and δT is defined as $T_{obs}-T_{syn}$. From this table, we see that the velocity structure derived by using the travel times of Love waves are about one per cent exaggerated. Zhao et al. [1991] claim that TIP's crustal model is mainly for the southern part of the Tibetan Plateau, If we include the effects of the new origin times and locations given here, the crustal velocity structure appropriate for the northern part of the Plateau is about three per cent slower than indicated by TIP.

In conclusion, we investigated more than 90 per cent of the Tibetan earthquakes and found that most of these events are shallower than reported by ISC; most are no deeper than 20 km. We relocated 59 of them, and found that the average origin time is 3.06 seconds earlier than that reported by ISC. Eleven of them are more than 5.5 seconds earlier than reported. Applying these corrections to P_n and S_n travel times explains why many authors have over-estimated the upper mantle velocities beneath the Tibetan Plateau.

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