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The Depth of the Deepest Historical Earthquakes

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Abstract—We use P and S times listed in the International Seismological Summary to relocate 23 historical earthquakes (1927–1963) reported as occurring at or below 670 km. In all cases, our relocated hypocenters are shallower than the starting depths; furthermore, all events converge to 691 km or less, with a precision estimated at ±10 km. This study upholds the results of Stark and Frohlich, who had used $pP - P$ times of post-WWSSN earthquakes to constrain reliable hypocentral depths to no greater than 684 km. In particular, we reject Rothé's claim that a 1963 event in the vicinity of New Guinea occurred at a depth of more than 780 km.

Key words: Seismicity, Benioff zones, historical earthquakes.

Introduction

It is generally assumed that the maximum depth of earthquakes at the bottom of Wadati-Benioff zones is about 670 km; however, the exact pattern of cessation of seismicity, and its possible relationship with the structural discontinuity around the same depth, are not fully understood. These problems are of great importance, since they bear directly on the thermomechanical state of the downgoing slab; the mechanism which inhibits subduction at greater depth is believed to also control the penetration, if any, of the descending slab into the lower mantle. Whether the slab penetrates the deeper mantle, and if so to which extent, has repercussions on the scale of mantle convection, and therefore on the location, nature and configuration of geochemical reservoirs.

In this general framework, the question of the maximum depth of seismic activity at the bottom of Benioff-Wadati zones, is made more intriguing by the occasional reporting of earthquakes at depths greater than 670 km. In a recent paper, STARK and FROHLICH [1985] examined a large number of earthquakes with published depths greater than 650 km, and concluded that (i) no depth greater than 684 km could be determined from reliable $pP - P$ readings for post-1963 events; and (ii) the only depths reported from P wave readings in excess of 685 km were for recent (post-1963) events of low magnitude ($m_b = 4.4 \pm 0.3$), or for larger events predating the

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WWSSN; the latter (if they could be confirmed) would suggest that STARK and FROHLICH's [1985] study, limited to a 20-year span and mostly to smaller earthquakes, may suffer a bias from insufficient sampling. Therefore, in this paper, we seek to systematically extend their investigations to historical earthquakes. In the absence of reliable $pP - P$ data, we use a variety of computer relocation techniques utilizing published P and S times to refine hypocentral depth constraints. All our successful relocations converge to depths of 691 km or less, with a precision estimated at ±10 km; this result is not significantly different from STARK and FROHLICH's [1985], and thus our study fully upholds theirs.

Dataset

We conducted a systematic search for the deepest historical earthquakes by scanning the NOAA epicentral tape for all events with reported depths greater than (or equal to) 670 km. This search yielded 86 earthquakes for the period 1927–1985. In order to provide a study fully complementary to STARK and FROHLICH's [1985], we define a historical earthquake as one occuring prior to 1964. Our dataset then reduces to 29 'historical' earthquakes, covering the period 1927–1963.

In such an endeavor, it is particularly important to obtain as complete a dataset as possible. In theory, this could be achieved only by relocating *all* historical earthquakes, regardless of depth, in order to guard against the remote possibility that an earthquake reported as 'reasonably' deep (say 600 km), or even possibly as a shallow event, may actually turn out to relocate below 670 km. This gargantuan task being clearly infeasible, we compromised by considering, in addition to the above events, all historical earthquakes listed, but not studied, by STARK and FROHLICH [1985].

We thus include in our dataset two 1950 events in the Peru–Brazil border region, whose Preliminary Determination of Epicenters [PDE] locations, quoted by these authors, are 750 km, despite NOAA tape depths of only 650 km, and the 1958 event in the Celebes Sea quoted at 690 km. We could find no record of the January 27, 1961 event quoted by SYKES [1966] at 738 km, neither on the NOAA tape, nor in ISS bulletins. As for the August 4, 1927 event quoted at 680 km in Stark and Frohlich's Table 3, it is obviously our Event 1, on August 8.

We also include in the dataset an event on January 2, 1963 quoted by ROTHÉ [1969] at 786 km under the Caroline Basin, although most catalogues report it as of crustal depth, under New Guinea.

Our final dataset thus consists of 33 events; Table 1 is a compilation of their hypocentral characteristics, as reported originally on the NOAA tape. The magnitudes listed in Table 1 are mostly so-called 'Pasadena' magnitudes, which, because most of these events are smaller than magnitude 7, are believed to be equivalent to the long-period or broad-band body-wave magnitude m_B [ABE and KANAMORI, 1979].

Table 1

Historical events with NOAA tape depths 670 km or greater

			Original NOAA tape hypocentral parameters				
Event number	Date	Magnitude	Origin time (GMT)	Latitude (°N)	Longitude (°E)	Depth (km)	Region
1	08 Aug 1927	6.25	18:43:48	−7	124	680	Banda Sea
2	08 Nov 1930	6.9	03:22:40	4	122.5	670	Celebes Sea
3	03 Apr 1931	6.75	23:19:18	−20	179.75	680	South of Fiji
4	25 Aug 1933	6.5	09:26:05	−6	121	720	South of Celebes
5	29 Jun 1934	6.9	08:25:17	−6.75	123.75	720	Banda Sea
6	29 Jun 1934	6.25	12:34:45	−5.75	121.5	670	South of Celebes
7	26 Oct 1934	6.75	14:44:29	−6	124	700	Banda Sea
8	08 May 1938	5.75	14:40:35	−6	124	700	Banda Sea
9	20 Dec 1939	6.	13:04:06	−7	120	700	Flores Basin
10	22 Sep 1940	6.75	22:51:56	8	124	680	Mindanao
11	30 Jun 1943	6.75	10:49:02	−7	122	720	Banda Sea
12	26 Nov 1945		01:03:58	−11	−69	700	Peru–Brazil
13	08 Oct 1946	6.75	13:56:25	−25	178	670	Tonga
14	13 Jan 1949		08:47:34	−25.5	178	680	Tonga
15	18 Sep 1950		19:36:43	−8	−71	750*	Peru–Brazil
16	28 Dec 1950		14:17:26	−7.5	−71	750*	Peru–Brazil
17	04 Nov 1953		06:05:07	39.5	129	675	Sea of Japan
18	10 Jun 1954		18:36:49	−19	−179	750	Tonga
19	09 Nov 1954		11:35:25	42.1	142.4	800	Japan
20	13 Nov 1954		14:46:40	30	131.8	800	Japan
21	18 Nov 1954		12:46:30	42.25	141.6	800	Japan
22	11 May 1955		19:23:58	−7	123.5	700	Banda Sea
23	21 Jan 1956		13:38:44	−1.5	129.5	700	Ceram Sea
24	12 Mar 1957		17:21:47	−21.5	−179	700	Tonga
25	10 Oct 1957		03:46:59	−22	178.5	700	Tonga
26	15 Sep 1958	6.13	19:45:40	2.5	120.5	690†	Celebes Sea
27	14 Jul 1959		18:20:41	−21	−179	700	Tonga
28	07 Apr 1960		03:05:43	−21.37	−179.29	670	Tonga
29	11 Nov 1960		06:14:43	−19.84	−179.05	670	South of Fiji
30	07 Mar 1962	7.0	11:01:04	19.2	145.1	685	Marianas
31	26 Apr 1962		07:26:31	−17.8	−179.1	689	South of Fiji
32	02 Jan 1963	5.9**	14:57:38	1.0	137.0	786†	Caroline Basin†
33	20 Mar 1963	5.2	04:43:14	−20.0	−179.0	690	South of Fiji

* PDE quoted by STARK and FROHLICH [1985].
† ROTHÉ [1969].
** m_b measured in this study.

Table 2 lists other depth estimates found for these events in the literature. When available, the second depth listed is that reported in the Bulletins of the International Seismological Summary [ISS]. We also list, when available, depths assigned by Beno Gutenberg on the basis of his own hand-made relocations [B.G. in Table 2], as

Table 2

Relocations carried out in this study

	Depth (km)						Final relocation						
				This Study			Epicenter						
Event Number	NOAA Tape	ISS	B.G.	h_{float}	h_{rms}	h_{slope}	(°N)	(°E)	O.T. GMT	Depth (km)	Number of stations	rms (s)
1	680		680	631	630	633	−7.2	124.2	18:43:47	631	16	1.4
2	670		670	631	630	628	3.6	121.9	03:22:41	630	25	1.9
3	680		680	622	620	622	−19.8	179.4	23:19:20	621	23	1.8
4	720		720				ISS dataset insufficient for relocation					
5	720	680	720	622	630	629	−6.6	123.1	08:25:14	627	33	1.4
6	670	680	670	639	640	639	−5.6	121.2	12:34:46	639	24	1.6
7	700	650	700	670	660	665	−6.7	124.0	14:44:32	665	32	2.0
8	700	285	700	667	660	649	−6.5	123.8	14:40:33	659	22	1.6
9	700		700			Listed as 'undetermined shock' in ISS; no sufficient data available						
10	680		680	662	662	662	7.6	123.6	22:51:58	662	32	1.1
11	720		720	643	655	657	−7.0	123.1	10:49:04	652	24	1.5
12	700		640	640	640	640	−9.4	−71.4	01:04:14	640	18	1.5
13	670		670	567	570	567	−25.1	178.2	13:56:18	568	14	1.8
14	680		680	606	595	597	−25.6	178.2	18:47:31	599	26	1.6
15	750*	603		647	647	647	−8.3	−71.0	19:36:45	647	37	1.4
16	750*	667		657	657	657	−8.1	−71.2	14:17:28	657	27	1.3
17	675	610	610	583	580	583	39.3	129.7	06:05:16	582	37	1.3
18	750	667		692	690	688	−19.1	−179.3	18:36:50	690	38	1.6
19	800	80		67	67	67	42.2	142.4	11:35:27	67	29	1.4
20	800	80					No data listed in ISS; probable error					
21	800	80					No data listed in ISS; probable error					
22	700	667		687	695	692	−6.7	123.4	19:24:01	691	14	1.1
23	700						No data listed in ISS					
24	700						No data listed in ISS					
25	700						No data listed in ISS					
26	690†	690		640	640 ± 20	640	2.5	120.8	19:45:47	640	32	1.9
27	700						No data listed in ISS					
28	700						No data listed in ISS					
29	700						No data listed in ISS					
30	685	689		673	668	674	19.0	145.3	11:01:03	672	39	1.2
31	689	552		570	570	569	−17.7	−178.7	07:26:25	570	39	1.2
32	30	0	786†	<0	0	0	−4.3	135.0	14:56:02	30**	31	1.6
33	690	668		669	670	669	−20.0	−178.9	04:43:12	669	35	1.7

* PDE quoted by Stark and Frohlich [1985]. † Rothé [1969]. ** Preferred depth from pP (Figure 9).

reported on his personal annotated copy of the ISS [SEISMOLOGICAL SOCIETY OF AMERICA, 1980]. These depths are, not surprisingly, identical with those listed in GUTENBERG and RICHTER's [1953] '*Seismicity of the Earth*', but the former dataset is more complete, and thus superior. In all but two cases, the NOAA depths are identical to Gutenberg's, which merely expresses the fact that his solutions are a primary source of NOAA tape hypocenters.

Depth-Relocation Methods

In the absence of reliable $pP - P$ for historical earthquakes, we use exclusively P and S times published in the ISS. However, during the period 1956–1963, the ISS lists arrival times only for major earthquakes, and as a result, no data were available for events 23–25 and 27–29. Similarly, no data were given for events 20 and 21 (most probably mis-transcribed shallow shocks). In the case of Event 9, listed as an 'undetermined shock', the meager data available were insufficient to achieve any stable relocation, and there is actually no evidence that this earthquake must be deep. We attempted relocations for the remaining 24 earthquakes, through a combination of three methods to obtain hypocentral depth constraints.

With sufficient data, it is possible to leave the depth 'floating' as an unconstrained parameter to be adjusted by the relocation algorithm to a value h_{float}. An adequate dataset must include stations over a broad range of distances to offset the well-known trade-off between depth and origin time for equidistant stations. The improvement in hypocentral depths, when this method is used, comes from the advantage of systematic computer relocation (including the elimination of stations with large residuals, in our study those amounting to more than three times the standard deviation) over the hand calculations of both the ISS publishers and Gutenberg.

When the unconstrained depth relocation fails to converge, due to the singular character of the inversion, it is possible to obtain a depth estimate by optimizing the quality of constrained-depth relocations performed at a number of hypocentral depths. Specifically, we constrain the hypocentral depth at a particular value h, and invert the available dataset for the three remaining parameters (latitude, longitude, and origin time), achieving a root-means-square [r.m.s.] residual σ. We let h vary, and study the function $\sigma(h)$. The value h_{rms} minimizing σ is an estimate of hypocentral depth. This technique, introduced by KANAMORI and MIYAMURA [1970], has been successfully used in the study of historical earthquakes [*e.g.*, STEIN and OKAL, 1978].

Finally, the pattern of variation of residuals at individual stations, as a function of epicentral distance, can be used to assess whether a constrained depth is too shallow or too deep. Specifically, if an earthquake of true depth h_{true} is modeled as having depth h_0, the travel-time residual $o - c$ for a station at a distance Δ will be, at first order in $h_{\text{true}} - h_0$:

$$o - c = (h_{\text{true}} - h_0)\frac{\partial T}{\partial h}(\Delta) = -(h_{\text{true}} - h_0)\frac{\cos i_h}{v_h} \tag{1}$$

where i_h is the take-off angle to the station, and v_h the hypocentral velocity (either P or S). Since cos i_h increases with increasing Δ, the residual $o - c$ will decrease with distance if the depth has been underestimated, and increase with distance if $h_{\text{true}} < h_0$. An estimate h_{slope} of hypocentral depth can then be obtained in the following way: carry out a constrained relocation at depth h; regress the individual station residuals $o - c$ as a function of (cos i_h/v_h), and consider the slope a of the resulting straight line; study the function $a(h)$ when h is varied; find the estimate h_{slope} such that $a(h_{\text{slope}}) = 0$. In a previous study [OKAL *et al.*, 1985], we verified on a number of test cases the compatibility of the estimates h_{rms}, h_{slope} and h_{float} (when available).

Illustration and test of the methods on modern data

In order to illustrate the above methods, we first test them on a recent deep Tonga event. We selected for this purpose the February 10, 1969 deep shock, whose depth is given by the NOAA tape as 673 km, and by the ISC as 635 ± 6 km (from P times) and 670 ± 5 km (from $pP - P$ intervals).

Our floating depth for this event, using 39 P times is $h_{\text{float}} = 659$ km, with a standard deviation $\sigma = 1.48$ s. This result falls between the two ISC depths; it is noteworthy that most ISC residuals at local stations (less than 15° in epicentral distance) are positive, suggesting that the ISC depth from P times alone is too shallow.

The depth minimizing the r.m.s. residual σ is found by polynomial interpolation to be $h_{\text{rms}} = 658$ km. Figure 1 shows the principle of this method; it should be noticed that while it can provide a rapid estimate of the hypocentral depth of an event, it loses resolution in the immediate vicinity of the true depth, because of its intrinsic nature as an extremum method (the derivative $\partial\sigma/\partial h$ vanishing exactly at the true depth). As a consequence, the depth h_{rms} is occasionally poorly constrained (see for example Event 26 below).

The depth h_{slope} is found to be 659 km. Figure 2 illustrates the principle of the method: we present in the top frames two cases of grossly inaccurate depth estimates: 300 km (much too shallow) and 780 km (much too deep). The slopes of the regressed trends of the individual residuals $o - c$ as a function of (cos i_h/v_h) are themselves plotted as a function of the constrained depth estimate in the lower frame. This plot can be interpolated for h_{slope}.

Because listings in all ISS and most ISC bulletins are given to a precision of $\delta t =$ 1 s, and the range of cos i_h is 2, constrained depths giving a slope of residuals less than ($\pm(1/2)v_h\,\delta t = 5$ km) are not significantly worse solutions than the interpolated h_{slope}. This remark can be used to provide an estimate of the precision of h_{slope}. In most cases, this turned out to be ±10 km. In all cases, this window includes all three

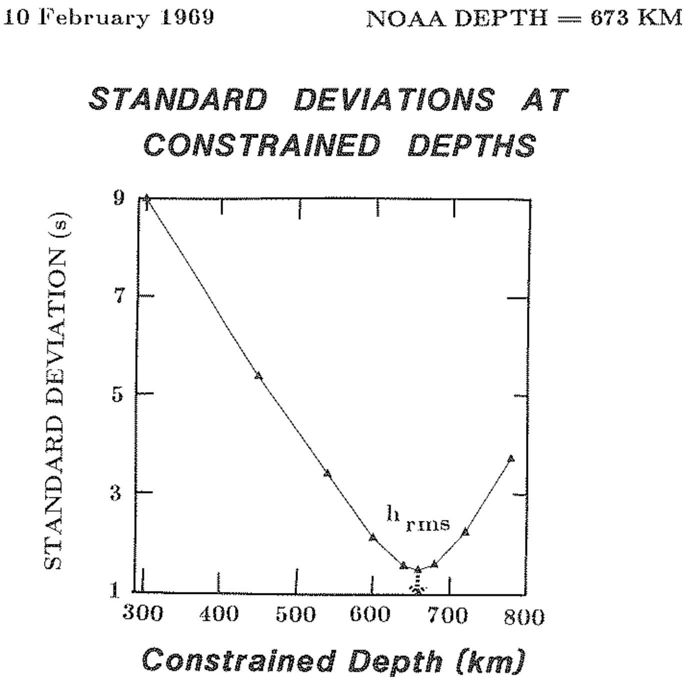

Figure 1

Determination of h_{rms} illustrated in the case of a modern event. The standard deviation σ of the residuals $o - c$ at the various stations is plotted as a function of depth. h_{rms} is the depth minimizing σ.

depth determinations, and we adopt it as a measure of the precision of our relocations.

The quality of the azimuthal distribution of stations used in the relocations is variable. In particular, events in Tonga are poorly covered in the East and South directions, while earthquakes in the Banda Sea, Peru–Brazil and Japan subduction zones have better azimuthal coverage. It is difficult to assess quantitatively the possible influence of such repartitions on the final relocations, beyond simply quoting BARAZANGI and ISACKS' [1979] and ENGDHAL *et al.*'s [1982] general conclusions that locations of slab events based on teleseismic rather than local travel-times are minimally affected by slab structure and biased azimuthal distributions.

Results

Table 2 lists the various depths h_{float}, h_{rms}, and h_{slope} obtained for 23 events. We failed to obtain convergence by any of the above methods for Event 4, due to an extremely limited dataset, and were unable to understand the rationale behind

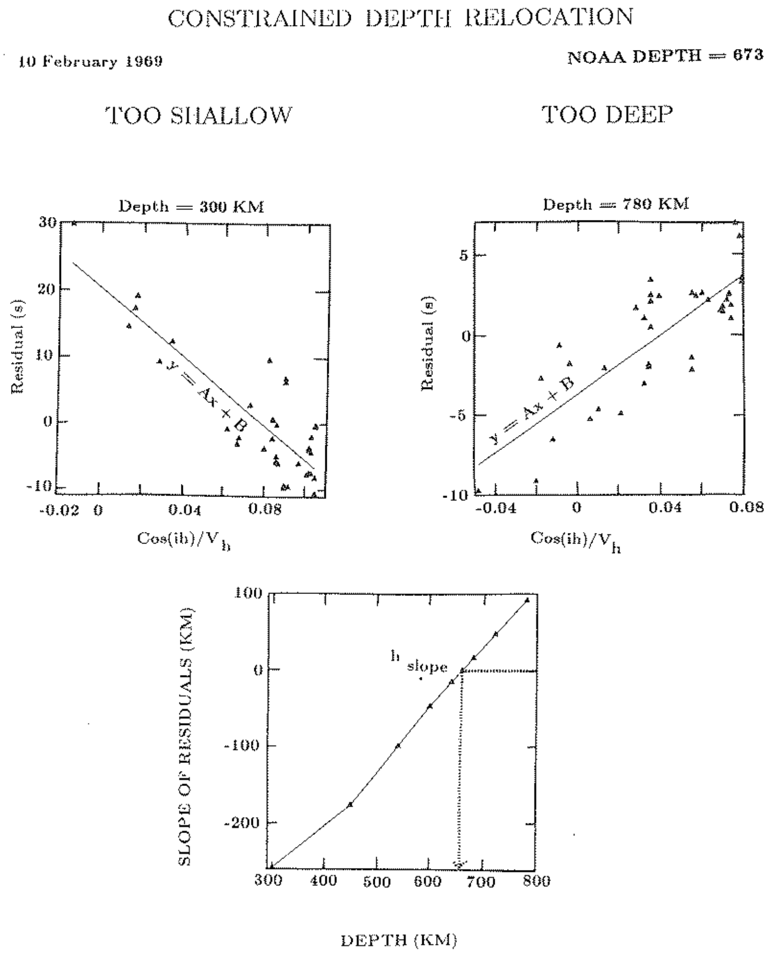

Figure 2

Determination of h_{slope} illustrated in the case of a modern event. The top frames show the trends of residuals *vs.* distance at individual stations for a constrained depth either too shallow (left) or too deep (right). The bottom frame shows the variation of the slope of the regressed trends, as a function of constrained depth. h_{slope} is the depth for which the slope vanishes.

Gutenberg's assignment of a depth of 720 km. The last six columns in Table 2 list a final relocation. Except in the case of Event 32 (see below), the preferred depth is the average of the three depths for each individual earthquake. We also provide the final epicenter, since in a few cases, relocation resulted in a significant change in coordinates. It is important to note that the residuals ($\leqslant 2.0$ s) are comparable to the best cases of historical, and for that matter modern, earthquake relocations.

Our most important result is that **all earthquakes** relocate shallower than their starting depths, and that the deepest relocation is 691 km. In this respect, and given our precision, we regard our results as perfectly consistent with STARK and FROHLICH's [1985].

Event 19, at 800 km the deepest historical event ever recorded, is obviously the result of a transcription error during the production of the NOAA tape. STARK and FROHLICH [1985] note that the original JMA bulletin lists it at 80 km depth. So does the ISS, and our relocations converge on a very similar figure (67 km). It is most probable that its aftershock, Event 21, as well as Event 20, also transcribed from the same monthly JMA bulletin, are similarly shallow shocks, at about 80 km depth. These shallow depths are also in agreement with the local trends of the Benioff–Wadati zones. This typographical error stresses the extreme caution which must govern the scientific use of computerized catalogues of historical data.

Discussion

Figures 3–8 are seismicity maps and cross-sections, with which we analyze our results in the framework of the more recent (and hopefully better located) seismicity in each of the subduction zones involved. On each of these figures, plus signs are all post-1962 earthquakes with NOAA tape depths of at least 550 km. Solid squares are the initial NOAA locations of our relocated events, and solid triangles, their final relocations. Asterisks indicate the reported location of the events which we could not relocate for lack of data. Each figure is comprised of a map, and two cross-sections, one parallel and one perpendicular to the strike of the Benioff–Wadati plane. In the case of the Korea–Sea of Japan region, the minimum depth is taken as 500, rather than 550 km, to reflect the shallower extent of the slab; in the case of the Tonga–Fiji region, only earthquakes with $m_b \geqslant 5$ are plotted.

We also compare our data to the centroid depths obtained by moment tensor inversion (the so-called 'Harvard solutions'), and published in the recent *Bulletins* of the PDE.

Fiji–Tonga

In this region, and as shown on Figure 3, all our events relocate inside the seismically active volume. The greatest relocated depth, 690 km, is obtained for Event 18 (10 June 1954) at the Northern end of the arc. Its location is less than 70 km away from the deepest well-constrained recent earthquake (17 June 1977), for which STARK and FROHLICH [1985] found a depth of 684 km and GIARDINI [1984] gave a centroid depth of 694 km. In this respect, our study confirms this portion of the Fiji Benioff–Wadati zone as one of the deepest centers of seismicity on Earth. In the case of Event 33 in the same area, the focal process involves two shocks separated by only 150 s, a time strikingly close to the typical $pP - P$ at teleseismic distances. The first

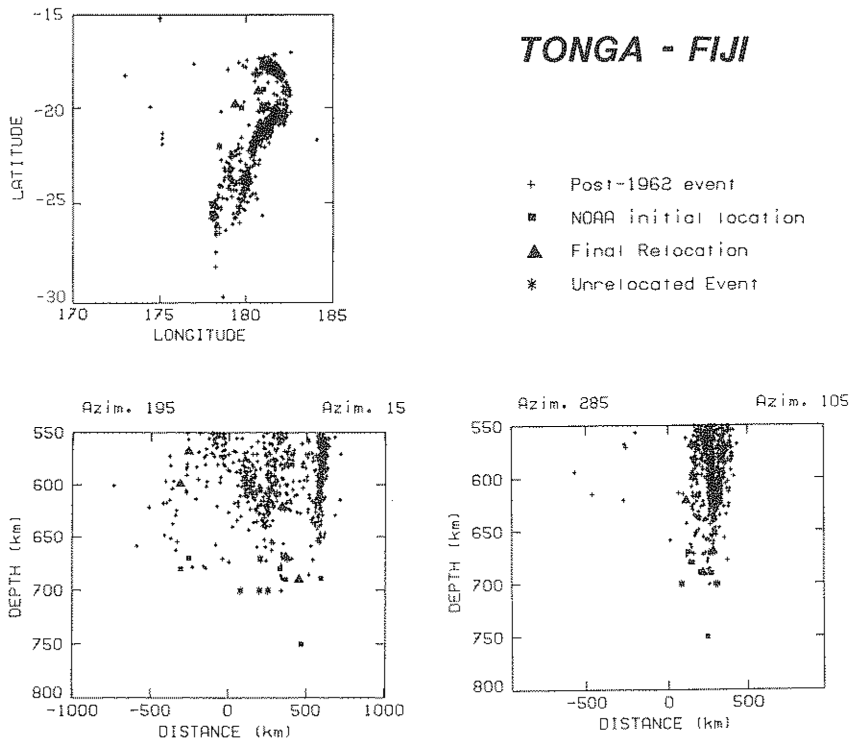

Figure 3

Relocation results in the Tonga–Fiji region, superimposed on post-1962 seismicity. Crosses are recent (post-1962 events) reported at depths of at least 550 km, and with $m_b \geqslant 5$. Squares are initial locations for our relocated events; triangles are final relocations; asterisks are reported locations of events which could not be relocated. *Top left:* Map view; *Bottom:* cross-sections at azimuth parallel and perpendicular to the strike of the Benioff–Wadati plane.

event relocates satisfactorily at 669 km. When attempting to relocate the second shock, a somewhat greater depth (704 km) is obtained. However, we cannot be sure that late arrivals are correctly assigned in the ISS as first arrivals of the second shock; for this reason, we do not regard the data for the second shock as significant. Further insight may be provided through techniques such as body wave modeling [LUNDGREN *et al.*, 1986]. All other Tonga events relocate to depths of 640 km or less.

Peru–Brazil

Figure 4 shows that the original depths in this region (700 and 750 km) were clearly excessive in the context of recent seismicity, for which the deepest hypocenters

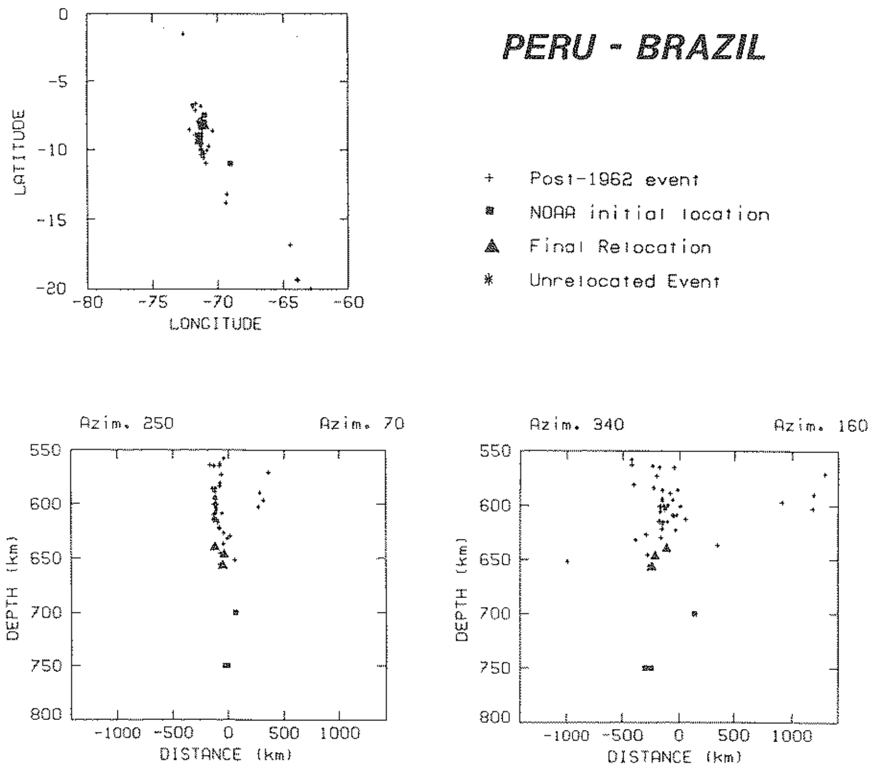

Figure 4

Same as Figure 3 for the Peru–Brazil region. No magnitude threshold is applied.

are at 655 km, and the greatest centroid depths obtained from moment-tensor inversion, 628 km. Our relocations bring the hypocenters back to 640, 647, and 657 km respectively; these figures fall within the range of recent seismicity. Furthermore, a clear improvement is achieved in the epicenter of Event 12, which is moved about 200 km back into the cluster of very deep seismicity.

Korea–Sea of Japan

Figure 5 shows still another example of successful relocation of an event into a small volume with recent seismicity. Event 17 relocates within 30 km of a large 1975 event (h = 560 km), and within 45 km of a 1982 event reported at 590 km.

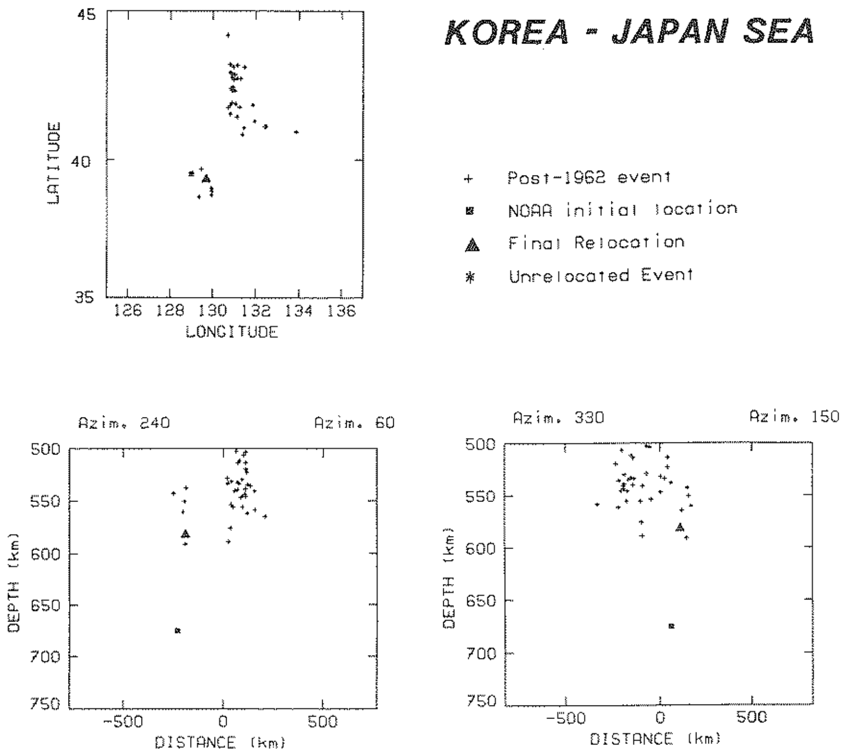

Figure 5
Same as Figure 4 for the Korea–Japan Sea region. A minimum depth of 500 km is used.

Marianas

Our lone event in the Mariana arc (Event 30) relocates to 672 km. While the epicentral relocation is consistent with recent seismicity, the depth remains significantly (34 km) greater than for all recent seismicity in the area (Figure 6). Similarly, all centroid depths obtained by moment tensor inversion of large post-1977 events are at most 609 km. It is noteworthy that Event 30 was assigned a Pasadena magnitude (presumably equivalent to m_B) of 7.0, and there remains the possibility that this truly large event was followed by a 25-year episode of quiescence.

Celebes and Mindanao

We relocate three events in this extremely complex area, involving several subduction zones of differing polarities. Figure 7 shows that Events 2 (in the Celebes Sea) and 10 (Mindanao) relocate in recently active areas; Event 26 (15 Sep 1958) relocates about 100 km west of the recently active region; however, its depth is

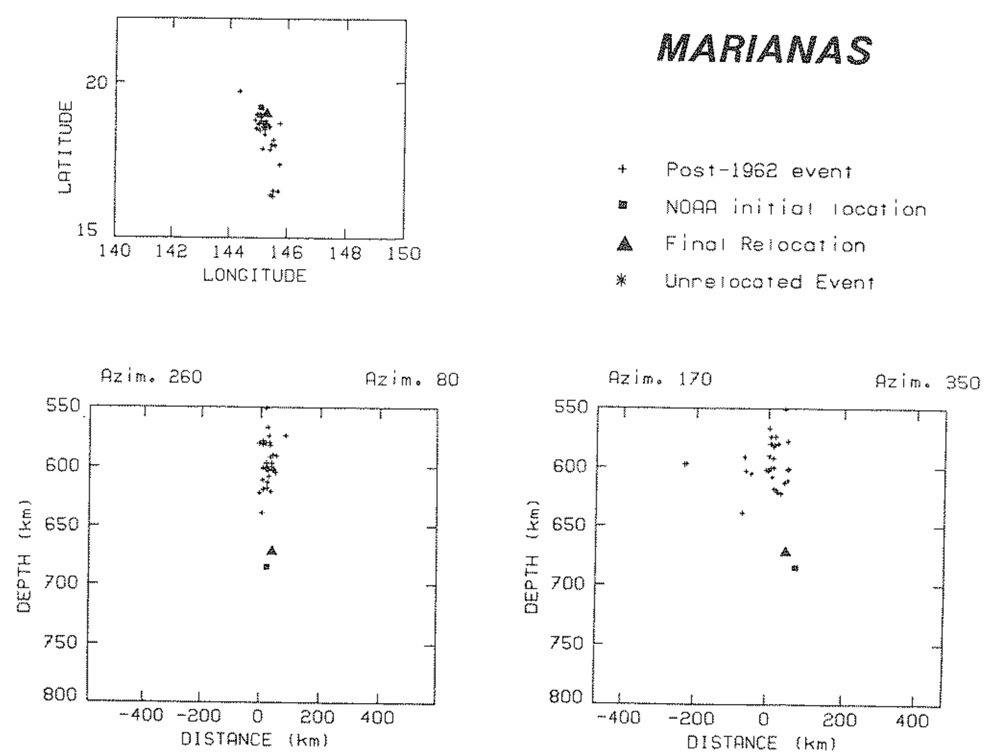

Figure 6
Same as Figure 4 for the Marianas region.

consistent with the deepest seismicity of the area. Centroid depths obtained from moment tensor inversion of recent earthquakes (645 km in Mindanao; 624 km in the Celebes Sea) are also consistent with our results.

Banda Sea

This region alone features nine historical earthquakes with reported depths greater than 670 km. We obtained relocations for six of them. All but one have relocated hypocenters at depths of 630–665 km, consistent with the recent seismicity, as shown on Figure 8. On the other hand, Event 22 (11 May 1955) relocates at 691 km, about 25 km deeper than the deepest recent seismicity. Similarly, the deepest centroid depth among the Harvard solutions is 656 km, 35 km above the solution for Event 30. It is noteworthy that this event features one of our poorest datasets (only 14 arrival times), and differences of up to 8 km exist between the various depths obtained, the floating depth being the shallowest (687 km). Present-day seismicity suggests that this earthquake may have been shallower.

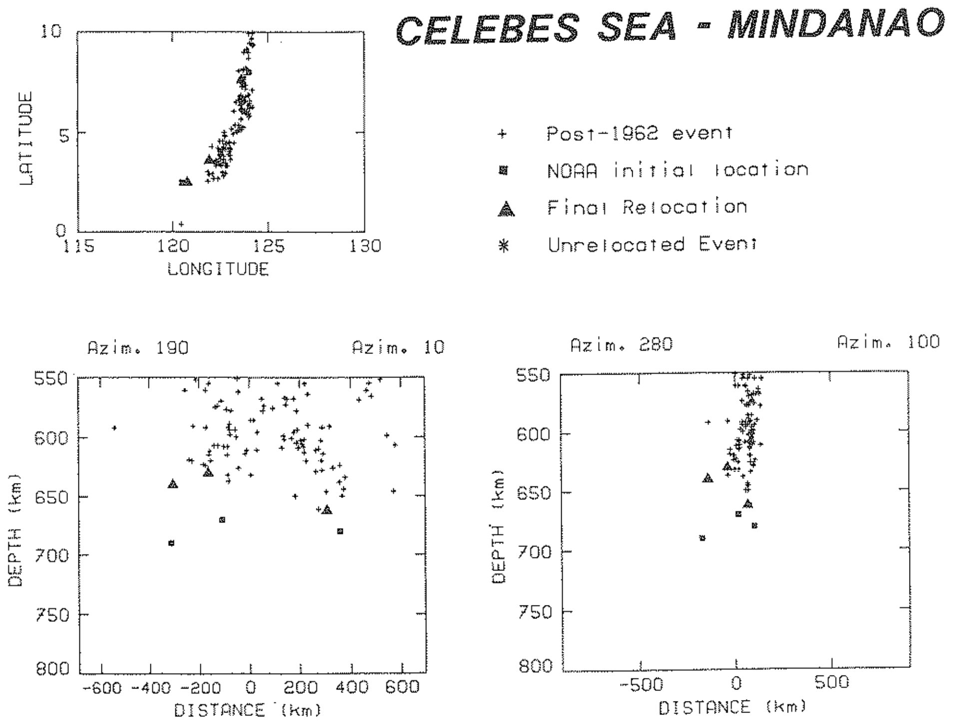

Figure 7
Same as Figure 4 for the Celebes Sea–Mindanao region.

An interesting case is that of Event 5 (29 June 1934), which for a long time was deemed the deepest earthquake ever recorded. The NOAA tape reports the value given by Gutenberg and Richter (720 km), and the ISS gives a depth of 680 km. However Jeffreys [1941] noted that Gutenberg and Richter's solution gave unsatifactory residuals, and relocated the earthquake at $(0.0969 \pm 0.0007)R$, or 647 ± 5 km. Our solution (627 ± 10 km) is close to his. It is not clear what led Gutenberg and Richter to propose their deeper figure, and in particular to ignore Jeffreys' study.

A Special Case: The January 2, 1963 New Guinea Event

We conducted a detailed study of this event, for which a limited set of modern (WWSSN) data is available, in order to examine Rothé's [1969] contention of a depth of 786 km. If Rothé's hypocenter were to be confirmed, this would be an exceptional event, not only because of its extreme depth, but also since no earthquake deeper than 200 km is known in a radius of 800 km from its alleged location; the latter constitutes a strong case against Rothé's solution, but not necessarily a com-

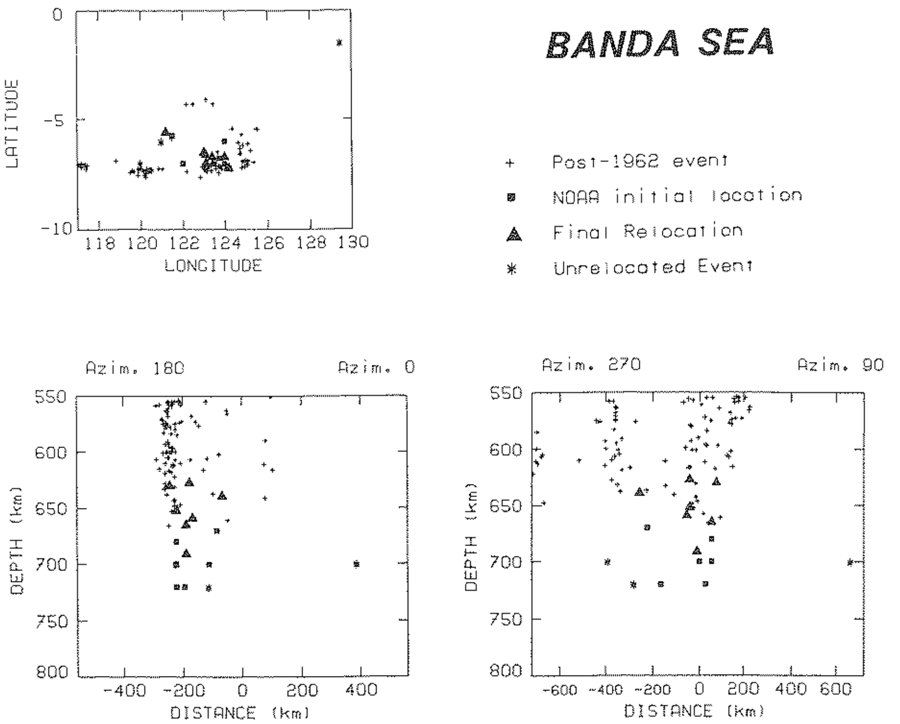

Figure 8
Same as Figure 4 for the Banda Sea region.

pelling one: for example, only one other earthquake deeper than 200 km is known in a comparable perimeter around the deep 1954 Spanish event. Thus, it is clear that an independent depth estimate for the January 2, 1963 earthquake is desirable.

On the basis of a dataset of 31 ISS listings, we were unable to obtain a positive unconstrained depth h_{float}. Similarly, the r.m.s. residual σ grows monotonically with depth from 1.6 s at the surface to more than 15 s at the depth proposed by Rothé. The same trend is observed for the slope of residuals a (h), which remains negative for all depths, and increases in amplitude with depth. All this indicates a very shallow focus, and any depth comparable to that suggested by ROTHÉ [1969] must be regarded as grossly incompatible with first arrival times. There remains the remote possibility of two events (one shallow, one deep) occurring within two minutes of each other, so as to confuse the identification of travel times; we do not see the necessity to invoke this model, since our relocation of the times published by the ISS converges satisfactorily on a shallow focus. It is worth noting further that our relocated epicenter, at 4.3°S, falls into a belt of shallow seismicity, inside New Guinea, more than 600 km from Rothé's epicenter.

Additionally, a clear second arrival is present on short-period signals from this event (Figure 9). It is tempting to interpret it as *pP*, which yields a depth of 30 km, our preferred figure reported in Table 2. The discrepancy between this figure and the depths h_{float}, h_{rms}, and h_{slope} (all zero), is probably an illustration of the poor modeling of the shallow structures in New Guinea by the Jeffreys–Bullen tables used in our relocation program. In the several records of this event available to us, we could not identify any arrival to be interpreted as *pP* or *sP* from a deep event. In short, we could not find any rationale behind the extreme value of the depth proposed by ROTHÉ [1969].

Conclusion

The great majority (20 out of 23) of our relocated events have final hypocenters inside three-dimensional regions of recent seismicity. The only exceptions are Event 26 in the Celebes Sea (consistent depth, but 100 km to the West), and Events 30 in the Marianas and 22 in the Banda Sea (respectively 34 and 25 km deeper than recent seismicity). This situaton is especially puzzling in the case of the Banda Sea event; our relocated depth would imply that the seismicity of this region is as deep as that of Fiji, a situation upheld neither by post-1962 seismicity, nor by recent centroid depths.

The most important conclusion of this study remains that all 23 successfully relocated events move to depths of 691 km or less. Our estimated precision (±10 km) makes this result fully consistent with STARK and FROHLICH's [1985] report of the deepest reliable $pP - P$ as 684 km (South of Fiji, 17 June 1977). One of our relocated events is found at 690 km in precisely the same area, also identified by GIARDINI [1984] as featuring the deepest centroid depths obtained by automated moment tensor inversion.

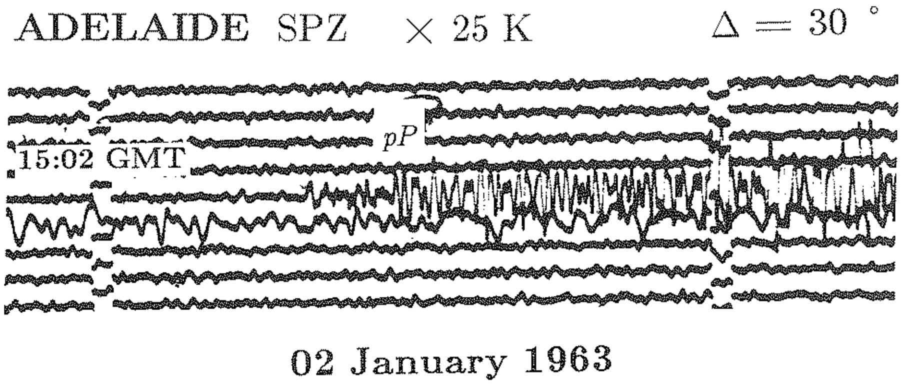

Figure 9

Close-up of the short-period vertical WWSSN record of Event 32 at Adelaide, Australia: Note strong second arrival, suggesting depth of 30 km if interpreted as *pP*.

Acknowledgements

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