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SEISMIC COUPLING AND OUTER RISE EARTHQUAKES

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Abstract. Variation of interplate seismic coupling at subduction zones is a major factor controlling the size of the largest underthrusting events. This variation also has a profound effect on the regional intraplate stresses in the vicinity of the subduction zone. Outer rise seismicity is strongly correlated with variations in interplate coupling, reflecting the stress state of the interplate coupled zone. Over 200 outer rise earthquakes with known focal mechanisms are used to investigate the relationship between stresses in the outer rise and interplate seismic coupling. These events occur within the downgoing (i.e., oceanic) plate near the bathymetric trench axes and generally fall into the categories of tensional (normal) or compressional (thrust) with their tensional or compressional stress axes oriented approximately horizontal and perpendicular to the trench. In uncoupled subduction zones, only tensional outer rise earthquakes occur, which indicates that the outer rise is dominated by tensional stresses associated with plate bending and/or slab pull forces. In strongly coupled subduction zones, both tensional and compressional outer rise events are found. These events are related both spatially and temporally to the distribution of large underthrusting earthquakes and are thus an integral part of the earthquake cycle. In the strongly coupled regions, tensional outer rise events follow large underthrusting events as the outer rise is temporarily in tension due to the underthrusting motion. Compressional outer rise events take place as compressional stress slowly accumulates oceanward of locked sections of the interplate zone. In four instances, compressional outer rise earthquakes have been followed by large underthrusting events which have occurred 2, 4, 7, and 19 years after the associated outer rise event. The remaining compressional outer rise events are located in regions that are either known seismic gaps or in regions where the seismic potential is unknown. The occurrence of compressional outer rise earthquakes suggests that compressional stress is accumulating in the adjacent interplate region and that there is the potential for a future large underthrusting event in the region. Thirty compressional outer rise events have been located in trench segments of Middle and South America, the Kurile Islands, the Tonga and Kermadec islands, the New Hebrides Arc, and the Solomon Islands regions. In both the southern Kamchatka and northern New Hebrides regions the outer rise seismicity indicates that the stress regimes in the outer rise have changed with time from tensional, following a previous large underthrusting event, to compressional at present. Thus three stages of the cycle from underthrusting to tensional outer rise regime to compressional outer rise regime are present, requiring only the occurrence of the next underthrusting event to complete the cycle. The occurrence of compressional outer rise events is useful for assessing the seismic potential of a region on an intermediate time scale.

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Introduction

In this paper we define outer rise events as earthquakes which are located within the oceanic plate in the vicinity of the trench axis (i.e., oceanward of the interplate coupled zone). These events fall into two main categories; compressional (thrust) events and tensional (normal) events with their compressional or tensional stress axes oriented approximately horizontal and perpendicular to the trench. The terms "trench earthquakes" and "bending earthquakes" have also been used by various authors to describe these events.

The occurrence of outer rise earthquakes was noted and explained in a tectonic framework by Stauder [1968a,b]. In these papers, Stauder studied events located under the Aleutian trench with normal focal mechanisms (tensional stress axes perpendicular to the trench) and suggested that these events were caused by stresses in the subducting oceanic plate due to the bending of the plate. These particular outer rise events were associated with the aftershock sequences of the great 1957 Aleutian and 1965 Rat Islands underthrusting events. In a later paper [Stauder, 1973], tensional outer rise events were also found to follow the great 1960 Chilean underthrusting event. Kanamori [1971a] and Abe [1972a] studied two very large tensional outer rise events (March 2, 1933, Sanriku, $M_W=8.4$ and March 30, 1965, Rat Islands, $M_S=7.5$, respectively) and proposed that these events, which may have ruptured through the entire oceanic lithosphere, occurred in response to the pull of the downgoing slab.

Bathymetric and gravity profiles across the outer rise bulge have been modeled extensively in the hope of constraining the mechanical properties of the lithosphere. Some models require large regional stresses to match the outer rise profiles [Hanks, 1971; Watts and Talwani, 1974; McAdoo et al., 1978], while others rely on the bending moment supplied by the subducted slab [Parsons and Molnar, 1976; Caldwell et al., 1976; Turcotte et al., 1978; Chapple and Forsyth, 1979]. Unfortunately, models using a wide range of plate thicknesses and rheologies are able to satisfy the observations. Plate bending models predict a tensional regime near the surface of the bending plate which agrees in principle with the many examples of tensional outer rise events; however, many of these models predict unrealistically large tensional stresses.

The plate bending model was further developed by Chapple and Forsyth [1979] by using the idea that the bending stresses would produce both a tensional and compressional region, separated in depth by a nodal surface. Their interest was to determine the depth of this nodal surface using the known occurrences of tensional and compressional outer rise events in order to constrain possible lithospheric models of the oceanic plate. Chapple and Forsyth [1979] settled on a depth between 30 and 40 km for the global average depth of the nodal surface. Christensen and Ruff [1983], Ward [1983, 1984], Dmowska and Lovison [1988], and Dmowska et al. [1988] have all suggested that stresses in the outer rise can vary both spatially and/or temporally due to the influence of the regional stress state. Ward [1984] shows calculations suggesting that the addition of regional stresses to an elastically bending plate model can move the neutral surface up to a depth of ±20 km without significantly changing the plate profile or increasing the maximum internal stress. The regional stresses referred to in this paper are not necessarily related to the long-term force system that forms and sustains the shape of the outer rise; but are short-term changes in stress which we propose are the direct cause of outer rise seismicity and are controlled by interplate coupling. We suggest that these stresses vary both spatially and temporally and are an integral part of the earthquake cycle.

Christensen and Ruff [1983] proposed a model in which the stress regime in the outer rise varies both temporally and spatially due to the cyclic influences of large underthrusting earthquakes on the regional stresses. In this way, the occurrence of outer rise events is related to the coupled and uncoupled nature of subduction zones. This model, which was based mostly on events in the list from Chapple and Forsyth [1979], suggests the following: In subduction zones which are inherently uncoupled and constantly in tension from slab pull, only tensional outer rise events are found. These events can occur at any time and are not necessarily related to seismic activity along the plate interface. In more strongly coupled subduction zones both tensional and compressional outer rise events are found. Tensional outer rise events occur following large subduction events when tensional stress from slab pull is transmitted to the outer rise. Compressional outer rise events occur in regions that are locked and have accumulated compressional stress in the outer rise through movements in adjacent subduction zone segments; many such regions would be recognized as seismic gaps. The types of occurrences that our model would predict have been summarized in Table 1 and have been graphically displayed in Figure 1.

In this paper we will further develop the ideas presented by Christensen and Ruff [1983] using a much expanded data set and also examine the relative effects of bending and regional stresses. We will show that the outer rise is a dynamic region where the stress state changes in both time and space, over relatively small distances, and is controlled by interactions at the plate margins.

Variations in seismic coupling have been discussed by many authors [e.g., Kanamori, 1971b, 1977; Kelleher et al., 1974; Uyeda and Kanamori, 1979; Lay and Kanamori, 1981; Lay et al., 1982; Ruff and Kanamori, 1980, 1983b]. Although the degree of coupling can be attributed to many factors, the results of coupling are most easily observed as variations in the size of the largest events that occur in a region [Kanamori, 1971b; Uyeda and Kanamori, 1979], with the largest events occurring in the most strongly coupled zones. Ruff and Kanamori [1980, 1983b] characterized the coupling of the various subduction zones by comparing their characteristic maximum earthquake size. The characteristic maximum earthquake size is simply the moment magnitude (M_W) of the largest earthquake to occur in a given subduction zone and is taken to be a characteristic property of that region. In Table 2 the subduction zones are listed in order of their characteristic maximum earthquake size (CMES) ranging from the highest of 9.5 in the southern Chile subduction zone to the lowest of 7.0 in the Scotia Arc. Obviously this type of ranking is biased by the short amount of time from which the observations are derived and also by the inadequate magnitude data for historic events. For example, Newcomb and McCann [1987] suggest that the Sumatra subduction zone is capable of producing an underthrusting event much larger than has been previously expected for the region (CMES = 7.9). Nevertheless, this ranking scheme generally agrees with accepted ideas of coupling in subduction zones and correlates well with other observable features [see Ruff and Kanamori, 1980, 1983b; Kelleher et al., 1974; Lay et al., 1982; Uyeda and Kanamori, 1979]. While we might expect minor changes in the ranking of subduction zones by characteristic maximum earthquake size as new data become available, we would not expect major changes in the order. In Table 2, three categories have been identified for future reference; strongly coupled (CMES ≥ 8.5), intermediately coupled (7.9 ≤ CMES < 8.5), and weakly coupled (uncoupled) (CMES < 7.9). Although the Philippines subduction zone is not assigned a CMES

TABLE 1. Types of Outer Rise Event Occurrences Predicted by the Model

Type of Event	
Tensional Outer-Rise Events	1. Events occurring in uncoupled regions showing no correlation to subduction zone activity
	2. Events occurring after and adjacent to large underthrusting events
Compressional Outer-Rise Events	1. Events occurring in known or suspected mature seismic gap regions
	2. Events occurring in unknown regions which may suggest a high seismic potential
	3. Events followed by large underthrusting events (i.e., known or unknown seismic gaps which fail)

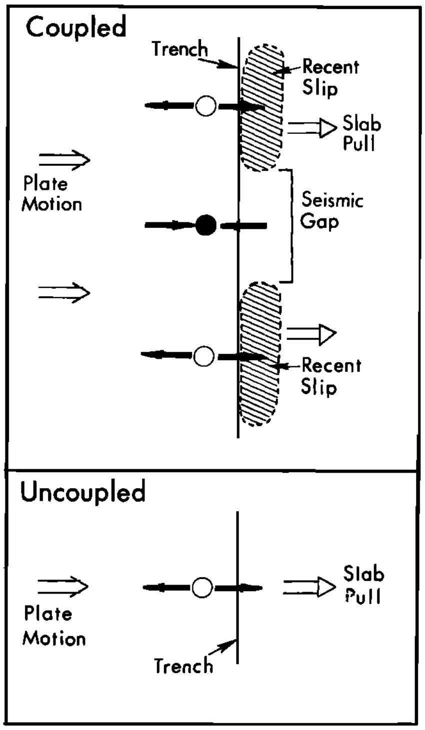

Fig. 1. Schematic representation of proposed model for (top) coupled and (bottom) uncoupled subduction zones. Map view of idealized subduction zones with subduction occurring from left to right. Recent large shallow underthrusting earthquakes are represented by shaded regions. Compressional outer rise events are shown as solid symbols, and tensional events are shown as open symbols; arrows depict the orientation of the principal stress axes.

by Ruff and Kanamori [1980] and thus does not appear in Table 2, we consider it to be in the weakly coupled category. The correlation of this ranking scheme with various aspects of outer rise seismicity will be developed later in this paper.

Outer Rise Earthquakes

Outer rise seismicity is distinguished from other subduction zone seismicity by its proximity to the bathymetric trench. Events which occur between the trench and the outer rise are clearly located in the oceanic plate and therefore easily separated from interplate seismicity. Events which are located on the subducting side of the trench require additional constraints to separate them from possible underthrusting events or seismicity in the overriding plate. Focal mechanisms can usually be used to distinguish these events from possible underthrusting events; however, it is sometimes difficult to distinguish them from events in the overriding plate. In general, we have incorporated nonunderthrusting events which are located seaward of the interplate coupled region, usually within 50 km of the trench.

The data set that we present in this paper is a compilation from many sources and includes 214 outer rise events for which focal mechanisms have been determined. These events, which include 184 tensional and 30 compressional outer rise events, are listed in Table 3 in chronological order by subduction zone. In addition to events cited by Chapple and Forsyth [1979], events processed by the Harvard group from 1977 to 1986 make up a large portion of the data set. Individual references are listed in Table 3. The catalog includes a total of 22 large ($M_S \geq 7.0$) outer rise earthquakes and is complete for these events back to 1962. Many of these larger events have been studied individually by various authors or in the appendix. The locations of all outer rise events listed in Table 3 are shown in Figure 2, with compressional and tensional events plotted as solid and open symbols, respectively. The distribution of outer rise events is fairly continuous over the major subduction zones; however, the subset of compressional outer rise events is more restricted in its distribution. The basic temporal and spatial occurrences of tensional and compressional outer rise events will be briefly discussed in the following subsections. It is important to realize throughout this paper that the data set is not complete for smaller magnitude events ($M < 7.0$), nor is it complete for larger events prior to 1962. Event coverage in the various regions depends largely on published results and varies with time. In addition, focal mechanisms from the Harvard group for events occurring after 1977 have a very strong influence on the catalog. A rigorous statistical treatment of this data set, given its incomplete nature, has not been attempted.

TABLE 2. Maximum Characteristic Earthquake Size

Magnitude	Region
Category 1: Strongly Coupled	
9.5	Southern Chile
9.2	Alaska
9.1	Aleutians
9.0	Kamchatka
8.8	Colombia
8.5	central Chile
8.5	Kuriles
Category 2: Intermediately Coupled	
8.3	Tonga
8.2	Peru
8.2	northeast Japan
8.1	Central America
8.1	Kermadec
8.1	Solomon Islands
8.0	Ryukyu
7.9	New Hebrides
7.9	Sumatra
Category 3: Weakly Coupled (Uncoupled)	
7.8	New Zealand
7.5	Caribbean
7.2	Izu Bonin
7.2	Marianas
7.1	Java
7.0	Scotia

After Ruff and Kanamori [1980].

TABLE 3. List of Outer Rise Earthquakes, Chronological by Region

No.	Date	Origin Time, UT	ISC Location			Magnitude		Independent Depth Estimate	References	Tectonic Class T/C	Focal Parameters	References
			Lat.	Long.	Dep.	Mb	Ms				AZI,Dip,Slip/AZI,Dip,Slip	
Philippines												
P1	1/09/65	13:32	11.88N	126.26E	27	6.1	---	------------------		T	4, 47, -55/137, 53,-122	F70
P2	3/20/69	16:18	8.69N	127.35E	43*	6.1	6.1	------------------		T	199, 68, -57/319, 39,-143	F72
P3	10/31/75	08:28	12.47N	126.01E	50*	6.4	7.2	------------------		T	30, 50,-143/274, 63, -46	T
P4	1/15/77	10:49	12.99N	125.92E	42*	5.5	4.6	33.	HAR	T	128, 56, -91/311, 34, -88	HAR
P5	5/26/81	06:47	6.14N	127.50E	42*	5.7	5.2	10.,10-24	DW83,W	T	128, 41,-100/322, 50, -81	DW83
P6	7/20/83	22:57	6.00N	127.43E	47*	5.7	5.1	17.	D84A	T	348, 43, -73/145, 49,-105	D84A
P7	5/15/84	22:24	8.85N	127.14E	63#	5.5	---	43.	D85A	T	183, 44, -74/340, 49,-105	D85A
P8	11/23/84	21:29	11.99N	126.51E	30#	5.5	5.5	25.	D85C	SS T	270, 70,-176/179, 86, -20	D85C
Ryukyu												
R1	8/03/68	04:54	25.73N	128.50E	43*	6.4	---	------------------		T	24, 68,-116/257, 33, -42	F72
R2	12/12/81	04:52	23.96N	125.92E	7*	6.1	6.3	15.FIX	DW83	SS T	113, 75, -3/204, 87,-165	DW83
R3	3/19/84	03:04	25.40N	128.22E	38#	5.3	5.2	42.	D84C	T	64, 53, -36/177, 62,-137	D84C
R4	6/30/84	20:27	30.36N	132.06E	33#	5.3	4.9	24.	HAR	T	189, 54, -78/348, 38,-107	HAR
R5	9/02/84	18:27	26.51N	129.89E	33#	5.5	5.2	11.	D85B	T	5, 39,-108/207, 53, -76	D85B
R6	1/07/85	12:01	26.76N	131.27E	19#	5.2	4.5	10.FIX	PDE	SS T	79, 72, -10/173, 81,-161	PDE
R7	3/01/85	08:14	28.38N	130.88E	41#	5.2	---	31.	PDE	T	28, 36, -83/200, 54, -95	PDE
R8	3/02/85	08:45	30.65N	132.60E	31#	5.3	5.0	18.	PDE	T	6, 32,-100/197, 59, -84	PDE
R9	6/17/85	19:12	30.28N	132.68E	26#	5.8	5.3	10.FIX	PDE	T	23, 38, -67/175, 56,-106	PDE
Izu Bonin, Japan, Mariana Islands												
I1	3/02/33	17:31	39.2 N	144.5 E	---	8.2	8.3	0-70	K71	T	0, 45, -90/180, 45, -90	K71
I2	7/04/64	10:49	11.70N	144.57E	26	6.0	---	------------------		T	54, 53, -90/234, 59, -90	KS
I3	10/27/66	14:21	22.11N	145.90E	27*	6.0	---	------------------		T	139, 25, -90/319, 65, -90	KS
I4	4/05/67	02:34	20.00N	147.27E	45*	5.9	---	------------------		T	139, 57,-113/357, 40, -60	KS
I5	9/01/70	05:11	17.70N	147.65E	50*	6.3	6.4	------------------		T	126, 34,-132/355, 65, -66	C&F
I6	5/11/74	06:14	19.73N	147.34E	47*	6.4	5.9	------------------		T	127, 64, -95/318, 28, -80	C&F
I7	8/25/74	01:18	32.18N	142.37E	45*	5.9	5.6	6.	F	T	23, 57, -73/174, 37,-114	F
I8	4/05/77	10:42	11.99N	144.23E	50*	5.4	5.5	33.	HAR	SS T	30, 66, 177/121, 87, 24	HAR
I9	12/21/77	01:00	25.54N	143.25E	47*	6.3	6.8	26.	HAR	T	147, 28,-102/341, 62, -84	HAR
I10	9/04/82	07:56	15.56N	147.61E	45*	5.5	5.2	33.	D83A	T	342, 35,-116/193, 59, -73	D83A
I11	9/09/82	15:42	15.52N	147.56E	39*	5.4	5.1	10.FIX	D83A	T	355, 45,-101/191, 46, -79	D83A
I12	3/17/83	02:53	12.31N	144.00E	46*	5.6	5.5	12.	HAR	T	156, 50, -57/291, 50,-123	HAR
I13	11/22/83	02:07	12.12N	144.30E	39#	5.6	5.2	21.	D84B	T	59, 38, -95/245, 52, -86	D84B
I14	9/20/84	19:19	16.78N	147.17E	45#	5.7	5.5	10.FIX	HAR	T	188, 63, -80/347, 29,-108	HAR
I15	12/11/84	22:47	26.50N	143.71E	17#	5.3	4.7	30.	D85C	T	291, 51,-125/159, 51, -55	D85C
I16	6/01/85	02:03	12.17N	144.42E	23#	5.7	5.4	16.	PDE	SS T	165, 75, -17/260, 74,-164	PDE
Java, Sumatra												
J1	3/30/67	02:08	11.14S	115.36E	36*	6.0	---	------------------		T	90, 36, -90/270, 54, -90	F70
J2	11/21/69	02:05	1.94N	94.61E	20*	6.4	7.7	0.-20.	T	T	23, 86, 6/292, 84, 175	F72
J3	5/04/72	04:11	10.73S	113.65E	42*	5.8	---	10.	F	T	84, 66,-125/324, 42, -38	F
J4	5/28/72	01:55	11.05S	116.97E	45*	6.3	6.2	------------------		T	47, 55,-137/290, 56, -44	C&F
J5	9/07/74	20:43	9.80S	108.49E	60*	6.1	6.5	------------------		T	150, 55, -41/267, 58,-137	C&F
J6	8/19/77	05:08	11.21S	118.43E	54*	5.8	5.4	15.	HAR	T	64, 34,-133/292, 66, -66	HAR
J7	8/19/77	06:08	11.16S	118.41E	78*	7.0	7.9	23.	G	T	260, 24, -73/ 61, 67, -98	G
J8	8/19/77	20:20	10.96S	119.17E	42*	5.6	5.2	33.	HAR	T	59, 21,-109/259, 70, -83	HAR
J9	8/19/77	21:35	10.95S	119.21E	39*	5.5	5.1	33.	HAR	T	63, 36,-119/278, 59, -70	HAR
J10	8/20/77	09:21	11.19S	119.14E	33	5.7	5.8	16.	HAR	T	119, 36, -80/287, 55, -97	HAR
J11	8/20/77	19:16	11.10S	119.09E	33*	5.9	6.1	15.	HAR	T	82, 17,-102/275, 73, -86	HAR
J12	8/21/77	02:12	11.27S	118.97E	33	5.3	5.0	20.	HAR	T	121, 38, -71/278, 54,-104	HAR
J13	8/21/77	20:29	10.88S	119.25E	33	5.4	5.4	15.	HAR	T	48, 61,-134/291, 51, -39	HAR
J14	8/23/77	10:24	11.52S	117.62E	33	5.5	4.9	15.	HAR	T	200, 83, 141/296, 51, 9	HAR
J15	8/23/77	23:06	11.53S	118.21E	33	5.4	---	15.	HAR	T	59, 27,-133/284, 71, -71	HAR
J16	8/25/77	18:05	10.88S	119.26E	51*	6.0	6.0	22.	HAR	T	42, 34,-110/247, 58, -77	HAR
J17	8/26/77	08:26	10.92S	119.30E	33	5.5	5.7	33.FIX	HAR	T	46, 73,-137/300, 49, -23	HAR
J18	9/01/77	13:13	11.68S	117.47E	33	5.3	---	33.FIX	HAR	T	40, 24, -97/228, 66, -87	HAR
J19	9/02/77	10:36	11.04S	119.17E	74*	5.8	5.9	21.	HAR	T	87, 34, -76/250, 57,-100	HAR
J20	9/05/77	11:16	11.20S	118.24E	33	5.5	4.9	33.	HAR	T	118, 60, -54/243, 45,-135	HAR
J21	9/07/77	01:19	11.15S	119.59E	39*	5.3	4.9	15.	HAR	T	69, 22, -87/246, 68, -91	HAR
J22	9/23/77	05:57	11.29S	118.10E	34*	5.8	5.4	20.	HAR	T	75, 66,-122/311, 39, -40	HAR
J23	9/25/77	18:31	11.38S	117.21E	46*	5.4	4.9	33.	HAR	T	121, 50, -4/213, 87,-140	HAR
J24	10/05/77	18:04	11.66S	117.34E	33	5.4	---	33.	HAR	T	75, 30, -80/243, 60, -96	HAR
J25	10/05/77	18:51	11.34S	117.17E	33	5.5	4.8	33.	HAR	T	53, 72,-161/316, 72, -19	HAR
J26	10/12/77	01:22	11.23S	119.37E	37*	5.6	4.7	15.FIX	HAR	T	119, 37, -48/251, 63,-117	HAR

TABLE 3. (continued)

No.	Date	Origin	ISC Location			Magnitude		Independent	Refer-	Tectonic	Focal Parameters	Refer-
		Time, UT	Lat.	Long.	Dep.	Mb	Ms	Depth Estimate	ences	Class T/C	AZI,Dip,Slip/AZI,Dip,Slip	ences
J27	12/06/77	17:52	11.34S	118.22E	43*	5.5	5.6	15.	HAR	T	43, 49,-155/296, 72, -44	HAR
J28	4/10/78	20:52	11.39S	116.68E	59*	6.7	6.4	13.FIX	G	T	81, 45, -87/256, 45, -93	G
J29	7/24/79	19:31	11.16S	107.72E	32*	6.3	6.9	20.	G	SS T	65, 46,-180/334, 90, -44	G
J30	9/29/79	18:37	1.16N	94.20E	30*	6.2	6.8	39.	G	SS T	284, 88,-179/194, 89, -2	G
J31	2/28/82	17:52	11.46S	117.24E	16*	5.6	---	34.,6-12	D83A,W	T	74, 27, -97/262, 63, -86	D83A
J32	8/07/82	20:56	11.16S	115.42E	55*	6.1	6.2	18.	D83A	T	288, 45, -65/ 75, 50,-113	D83A
J33	11/11/82	00:43	6.61S	101.70E	96*	6.1	6.0	29.	D83A	T	108, 35,-135/338, 66, -64	D83A
J34	3/03/83	02:30	6.13S	100.73E	36*	5.5	5.4	42.	D83B	T	9, 58, -25/113, 69,-146	D83B
J35	4/16/83	12:57	10.19S	110.84E	54*	5.9	5.4	62.	D83C	T	90, 45, -95/277, 45, -85	D83C
J36	4/23/83	09:20	11.21S	118.92E	39*	5.5	---	47.	D83C	T	293, 42, -84/105, 48, -95	D83C
J37	9/29/83	02:06	11.37S	115.32E	40*	5.6	4.8	43.	D84A	T	70, 44,-128/297, 57, -60	D84A
J38	11/15/83	10:38	11.28S	115.32E	33#	5.4	---	52.	D84B	T	42, 59,-159/300, 72, -33	D84B
J39	11/23/84	04:45	7.99S	102.25E	33#	6.0	6.7	21.	NEIS	SS T	154, 71, 20/ 58, 71, 160	NEIS
J40	9/15/85	22:58	10.81S	119.30E	39#	5.4	4.0	42.	PDE	T	178, 12, -51/318, 81, -98	PDE
J41	10/23/85	00:49	11.11S	125.16E	14#	6.0	5.4	52.	PDE	T	3, 37,-102/198, 54, -81	PDE
								Caribbean				
CA1	3/30/84	07:59	17.38N	59.63W	6*	5.8	5.1	10.FIX	HAR	SS T	10, 76, -19/105, 72,-165	HAR
								Sandwich Islands				
SI1	6/16/81	18:56	56.14S	24.81W	53*	5.2	5.7	53.FIX	HAR	SS T	23, 71, -13/117, 78,-161	HAR
SI2	1/18/83	15:23	57.98S	24.35W	55*	5.8	6.4	28.	HAR	SS T	52, 61, 6/319, 85, 151	HAR
SI3	10/22/83	04:21	60.75S	25.60W	22*	6.4	6.8	10.FIX	HAR	T	42, 56, -95/231, 35, -82	HAR
SI4	10/22/83	13:07	60.69S	25.41W	44*	6.1	6.2	10.FIX	HAR	T	39, 64,-129/281, 46, -38	HAR
SI5	4/28/85	22:56	55.49S	26.15W	33#	5.7	5.6	10.FIX	HAR	SS T	76, 82,-142/339, 53, -11	HAR
								Solomon Islands				
S1	12/23/66	15:50	7.11S	148.31E	55*	6.1	---	-------------------		C	63, 30, 70/264, 64, 101	JM
S2	9/28/67	04:56	6.59S	153.47E	20	5.8	---	-------------------		T	310, 33,-103/142, 58, -82	JM
S3	9/14/71	05:20	6.46S	151.55E	50*	6.1	6.3	-------------------		T	52, 78,-122/302, 34, -22	P79
S4	8/17/72	23:44	6.04S	152.90E	26	6.3	7.1	0.-6.	T	T	95, 58,-115/316, 40, -56	T
S5	1/18/73	09:28	6.88S	150.03E	68*	6.3	6.8	-------------------		C	69, 28, 86/253, 62, 92	P79
S6	1/27/77	13:59	6.51S	152.86E	37	5.7	---	18.	HAR	T	73, 37,-106/273, 55, -78	HAR
S7	5/01/77	18:39	7.24S	154.44E	40	5.5	---	14.	HAR	T	138, 57, -72/287, 37,-116	HAR
S8	7/29/77	11:15	8.04S	155.56E	3	6.3	7.2	24.,0.-15.	G,T	SS	200, 88, 150/291, 60, 2	T
S9	12/06/81	12:50	6.14S	152.03E	60	5.9	6.1	15.FIX	DW83	T	91, 55, -83/259, 36,-100	DW83
S10	5/04/84	03:56	6.54S	152.64E	33	5.6	---	10.FIX	D85A	T	105, 43,-101/299, 48, -80	D85A
S11	6/07/84	21:52	5.99S	151.71E	33#	5.6	---	10.FIX	HAR	T	55, 78,-105/288, 20, -39	HAR
S12	12/11/85	12:15	7.02S	150.01E	13#	5.4	---	10.FIX	PDE	T	60, 56,-120/286, 44, -53	PDE
								New Hebrides				
N1	1/22/64	23:59	13.64S	165.96E	50	6.3	---	21.	CI	T	166, 60, -90/346, 30, -90	JM
N2	9/12/66	11:29	23.00S	170.60E	37*	5.9	---	18.,17.	CI,P78	T	60, 44,-143/300, 66, -52	JM
N3	12/30/73	16:39	15.37S	166.54E	10	5.8	6.6	-------------------		T	160, 56, -90/340, 34, -90	I81
N4	11/16/81	13:53	22.11S	169.52E	44*	5.7	6.2	15.FIX	DW83	T	132, 44, -90/311, 46, -90	DW83
N5	5/20/82	21:29	20.24S	168.20E	72*	5.8	5.8	21.	D83A	T	173, 34, -78/339, 56, -98	D83A
N6	9/09/82	16:40	22.05S	169.38E	31*	5.5	5.0	10.FIX	D83A	T	123, 19,-119/334, 73, -80	D83A
N7	10/19/82	16:19	11.39S	163.13E	35*	5.7	6.0	19.	HAR	T	65, 55, -81/229, 36,-103	HAR
N8	2/24/85	22:37	12.97S	165.72E	33#	5.2	4.6	10.FIX	PDE	T	152, 17,-111/354, 74, -84	PDE
N9	8/22/85	02:01	22.06S	169.46E	33#	5.2	4.7	30.	PDE	T	170, 70, -83/329, 21,-110	PDE
N10	10/21/85	02:36	13.60S	166.00E	33#	5.5	5.2	13.	PDE	C	158, 53, 77/359, 39, 107	PDE
N11	11/28/85	02:25	14.04S	166.24E	33#	6.0	7.0	24.	PDE	T	4, 56, -77/161, 36,-109	PDE
N12	11/28/85	03:49	13.99S	166.18E	33#	6.3	7.1	44.	PDE	SS T	167, 78, 158/262, 68, 13	PDE
N13	11/28/85	06:37	13.90S	166.29E	33#	5.6	5.8	10.FIX	PDE	T	8, 45, -90/188, 45, -90	PDE
N14	11/28/85	17:59	14.14S	166.22E	33#	5.2	---	23.	PDE	T	20, 29, -68/175, 63,-102	PDE
N15	11/28/85	19:04	13.81S	166.11E	33#	5.2	4.9	43.	PDE	T	6, 59, -97/200, 32, -78	PDE
N16	11/29/85	01:09	13.90S	166.16E	33#	5.2	5.2	22.	PDE	T	11, 65, -78/164, 28,-144	PDE
N17	12/16/85	08:04	14.07S	166.25E	37#	6.0	6.7	32.	PDE	T	28, 52, -61/166, 46,-122	PDE
								South America (Chile)				
C1	11/11/62	22:14	43.06S	75.82W	33	6.7	---	-------------------		T	35, 46, -76/195, 46,-104	S73
C2	8/05/64	22:23	41.13S	74.99W	7	6.1	---	-------------------		T	181, 68, -56/300, 40,-144	S73
C3	8/18/64	04:45	26.37S	71.78W	28*	6.4	---	-------------------		C	50, 40, 86/235, 50, 93	S73
C4	10/03/65	16:14	42.90S	75.13W	28*	6.1	---	-------------------		T	10, 70,-106/230, 25, -53	S73
C5	3/13/67	16:06	40.12S	74.68W	33*	5.9	---	-------------------		T	55, 70,-125/299, 40, -33	S73
C6	9/11/68	18:26	42.95S	75.21W	28*	5.7	5.5	-------------------		T	44, 75,-120/290, 33, -28	S73

TABLE 3. (continued)

No.	Date	Origin	ISC Location			Magnitude		Independent	Refer-	Tectonic	Focal Parameters	Refer-
		Time, UT	Lat.	Long.	Dep.	Mb	Ms	Depth Estimate	ences	Class T/C	AZI,Dip,Slip/AZI,Dip,Slip	ences
C7	11/13/69	07:51	27.76S	71.67W	43*	5.8	6.0	------------------		C	40, 78,-127/295, 39, -19	S73
C8	9/25/71	13:05	32.40S	73.06W	4	5.5	5.8	------------------		T	235, 65, -45/345, 50,-147	KM
C9	12/01/73	17:00	35.59S	74.54W	23	5.8	5.9	------------------		T	96, 36, -39/221, 69,-120	C&F
C10	2/22/77	14:10	45.39S	75.30W	33	5.1	5.4	10.FIX	HAR	SS T	168, 78, -14/261, 76,-168	HAR
C11	10/16/81	03:25	33.15S	73.10W	74*	6.2	7.2	0-20,12-24	CR85,W	C	6, 56, 86/194, 34, 96	DW83
C12	2/25/82	21:59	33.24S	73.25W	27	5.0	---	------------------		C	170, 74, 109/300, 25, 42	KM
C13	6/01/82	04:14	41.41S	74.97W	44*	6.0	6.1	10.FIX	D83A	T	160, 33,-130/ 25, 65, -67	D83A
C14	5/09/83	10:58	40.89S	74.92W	23	5.9	5.8	33.FIX	D83C	T	358, 41,-118/213, 54, -68	D83C
C15	11/28/83	19:10	44.87S	75.93W	26#	5.6	4.8	10.FIX	D84B	T	133, 18,-142/ 7, 79, -76	D84B
C16	5/25/84	13:20	42.65S	75.23W	31#	5.5	4.5	10.FIX	D85A	T	185, 27, -98/ 14, 63, -86	D85A
C17	6/03/84	01:44	45.26S	75.71W	33#	5.3	4.9	10.FIX	D85A	T	320, 61,-161/221, 73, -30	D85A
C18	3/30/85	13:47	45.53S	76.37W	33#	5.0	4.6	10.FIX	PDE	T	135, 64, -94/325, 26, -81	PDE
C19	4/28/85	08:30	39.73S	75.66W	10#	6.1	5.5	10.FIX	PDE	T	46, 27,-101/239, 64, -84	PDE
C20	6/14/85	13:14	40.77S	74.95W	33#	5.5	4.6	10.FIX	PDE	T	4, 49,-117/223, 48, -62	PDE
C21	8/04/85	04:54	44.88S	75.68W	28#	5.6	5.4	10.FIX	PDE	T	199, 24, -64/352, 68,-101	PDE
C22	11/06/85	16:08	40.50S	74.91W	33#	5.1	5.1	16.	PDE	T	221, 49, -52/351, 53,-125	PDE
								South America (Ecuador, Peru, and Colombia)				
E1	8/29/63	15:30	6.97S	81.48W	23	6.5	---	------------------		T	190, 41, -64/337, 54,-111	S75
E2	8/03/65	02:01	7.31S	81.27W	50*	5.8	---	------------------		T	207, 40, -59/340, 60,-118	S75
E3	9/03/67	21:07	10.59S	79.67W	29*	6.5	---	------------------		C	0, 60, 140/113, 56, 37	S75
E4	1/02/81	07:37	2.13N	79.16W	27*	5.7	5.7	15.FIX	DW83	T	26, 42,-128/252, 58, -61	DW83
E5	2/28/81	21:56	6.41S	81.39W	24*	5.3	6.0	40.FIX	DW83	C	340, 40, 74/181, 52, 103	DW83
E6	1/17/84	16:19	3.92S	81.41W	32*	5.9	4.8	13.	HAR	C	139, 47, 101/303, 45, 78	HAR
								Middle America				
M1	2/04/70	05:08	15.57N	99.48W	21*	5.9	6.5	------------------		T	3, 70, -67/136, 31,-136	C&F
M2	8/20/71	21:36	13.30N	92.41W	20*	5.8	5.6	19.	C&F	C	315, 62, 120/ 84, 40, 47	F
M3	9/16/72	09:14	15.23N	96.26W	26*	6.0	5.7	------------------		T	96, 41,-114/305, 55, -70	C&F
M4	8/17/81	02:18	14.43N	93.78W	35*	5.6	5.5	10.FIX	DW83	T	316, 15, -75/121, 75, -94	DW83
M5	11/24/82	10:23	12.78N	91.02W	27*	5.5	5.0	50.	D83A	T	127, 34, -76/291, 57, -99	D83A
								Aleutian				
A1	3/07/29	01:34	50.88N	169.71W	0	7.7	7.7	------------------		T	112, 42, -50/244, 59,-120	K72
A2	4/19/57	22:19	52.20N	166.28W	4	7.0	---	------------------		T	35, 55,-120/260, 45, -55	S68B
A3	2/22/58	10:50	50.32N	175.49W	0	6.7	---	------------------		T	35, 50,-123/260, 50, -57	S68B
A4	11/13/60	09:20	51.41N	168.86W	0	7.0	7.0	------------------		T	120, 50, -57/255, 50,-123	S68B
A5	8/02/64	08:36	56.18N	149.90W	31*	5.4	---	------------------		T	70, 80,-106/307, 19, -33	S68B
A6	2/06/65	01:40	53.14N	161.85W	43*	6.4	---	------------------		T	82, 52, -68/228, 43,-116	S68B
A7	2/06/65	16:50	53.26N	161.74W	33	6.1	---	------------------		T	82, 42, -81/251, 50, -98	S68B
A8	2/07/65	02:17	51.34N	173.44E	45*	6.0	---	------------------		T	114, 52,-116/332, 45, -61	S68B
A9	2/08/65	15:46	55.12N	165.60E	35*	5.6	---	------------------		T	177, 57, -32/283, 63,-142	C
A10	3/30/65	02:27	50.32N	177.93E	20	7.0	7.5	------------------		T	104, 47,-118/322, 50, -63	S68B
A11	7/29/65	08:29	51.11N	171.30W	18*	6.3	---	------------------		T	112, 42, -50/244, 59,-120	S68B
A12	10/01/65	08:52	50.02N	178.28E	37*	6.3	---	------------------		T	85, 50,-123/310, 50, -57	S68A
A13	6/02/66	03:27	51.01N	175.98E	48*	5.9	---	23.	FU81	T	121, 51,-102/320, 40, -76	S68B
A14	8/07/66	02:13	50.57N	171.22W	29*	6.2	---	------------------		T	95, 65, -67/230, 33,-130	S68B
A15	6/20/69	02:37	53.31N	162.41W	41*	5.8	5.1	14.	HJ	T	61, 43, -78/224, 49,-101	HJ
A16	2/27/70	07:07	50.13N	179.59W	7*	6.0	5.9	------------------		T	85, 78, -83/234, 14,-120	S72
A17	3/19/70	23:33	51.34N	173.75E	8*	5.8	6.2	------------------		T	125, 52,-112/338, 43, -64	F
A18	10/13/72	04:46	52.89N	162.98W	35*	6.0	5.4	10.	HJ	T	73, 43, -70/227, 50,-107	HJ
A19	8/02/75	10:18	53.48N	161.39W	46*	6.0	6.0	15.	HJ	T	5, 38,-133/235, 63, -62	HJ
A20	6/05/81	07:09	52.34N	165.21W	40*	5.6	4.2	10.FIX,6.-10.	DW83,W	T	42, 54,-140/285, 59, -44	DW83
A21	5/31/82	10:21	55.07N	165.40E	46*	5.8	6.7	19.	HAR	SS T	211, 81, -38/308, 53,-168	HAR
A22	7/27/84	15:57	50.32N	176.87W	33#	5.8	5.0	13.	D85B	T	65, 43,-130/294, 58, -59	D85B
A23	3/02/86	05:40	50.79N	179.18E	33#	5.4	5.3	15.FIX	HAR	SS T	60, 85, 166/152, 76, 5	HAR
A24	3/04/86	08:47	51.55N	166.94W	33#	5.6	4.6	38.	HAR	T	72, 43, -76/232, 49,-103	HAR
								Kurile Islands				
K1	9/15/62	22:50	48.48N	157.11E	3	6.5	6.5	------------------		T	45, 42, -95/232, 48, -85	UB
K2	3/16/63	08:44	46.79N	154.83E	0	7.7	---	10.-50.	T	C	16, 55, 90/196, 35, 90	SB66
K3	10/14/63	13:21	44.79N	151.13E	0	6.3	---	------------------		T	78, 11, -67/235, 80, -94	SM
K4	4/05/65	13:52	44.51N	150.90E	76*	5.6	---	25.	F	T	15, 81, 149/110, 59, 10	F
K5	7/25/65	13:33	41.24N	146.57E	31*	5.7	---	------------------		T	82, 46, -64/227, 50,-114	SH
K6	2/06/70	00:11	54.57N	163.56E	43*	5.6	5.3	------------------		T	199, 70, -80/352, 22,-115	C
K7	9/09/71	23:01	44.34N	150.85E	7	6.0	5.9	15.	F	T	103, 13, -38/230, 82,-100	SM

TABLE 3. (continued)

No.	Date	Origin Time, UT	ISC Location			Magnitude		Independent Depth Estimate	References	Tectonic Class T/C	Focal Parameters AZI,Dip,Slip/AZI,Dip,Slip	References
			Lat.	Long.	Dep.	Mb	Ms					
K8	12/02/71	17:18	44.77N	153.33E	38*	6.2	6.3	-------------------		C	215, 80, 100/348, 14, 45	SM
K9	2/01/81	22:43	53.02N	162.41E	43*	5.9	5.5	15.FIX,12-20	DW83,W	T	54, 32, -67/207, 61,-104	DW83
K10	4/30/81	14:41	43.23N	149.94E	49*	6.1	6.2	11.FIX,6-12	DW83,W	T	58, 60,-121/288, 42, -48	DW83
K11	8/23/81	12:00	48.71N	157.37E	33*	6.0	5.8	20.FIX,36-42	DW83,W	C	55, 41, 90/235, 49, 90	DW83
K12	10/01/81	17:04	50.72N	160.40E	28*	5.9	6.1	15.FIX,6-12	DW83,W	T	78, 44, -61/220, 53,-115	DW83
K13	6/30/82	01:57	44.56N	151.03E	45*	6.4	7.0	21.	D83A	SS T	131, 39, -1/222, 90,-129	D83A
K14	9/26/82	01:09	50.10N	158.63E	44*	5.5	4.7	10.FIX	D83A	T	101, 45, -54/235, 55,-121	D83A
K15	8/02/83	06:08	45.05N	153.36E	52*	5.5	5.1	35.	D84A	C	77, 20, 125/220, 74, 78	D84A
K16	4/10/85	20:37	49.99N	159.42E	28#	5.5	4.9	51.	PDE	C	0, 37, 59/216, 59, 111	PDE
K17	10/02/85	03:16	43.93N	151.37E	42#	5.4	4.4	17.	PDE	T	39, 54,-108/248, 40, -67	PDE
								Tonga-Kermadec				
T1	2/17/67	10:10	23.79S	175.14W	20*	6.1	---	-----------------		T	34, 34, -90/214, 56, -90	JM
T2	11/12/67	10:36	17.19S	171.98W	31*	5.6	---	42.	CF	C	215, 63, 120/343, 39, 45	CF
T3	12/27/67	16:22	22.46S	174.61W	33	5.8	---	-----------------		T	189, 76, -42/292, 50,-161	JM
T4	1/29/69	17:44	17.15S	171.57W	35*	6.0	5.6	-----------------		C	2, 18, 90/182, 72, 90	JM
T5	8/07/72	09:24	16.66S	172.01W	40*	5.8	6.0	45.	F	C	180, 45, 105/339, 47, 75	F
T6	9/27/72	09:01	16.47S	172.17W	10	5.8	6.0	6.	CF	T	207, 65, -43/319, 52,-147	CF
T7	7/02/74	23:26	29.22S	175.94W	33	6.5	7.2	5.-30.	T	C	65, 23, 137/197, 75, 73	C&F
T8	7/03/74	23:25	29.37S	176.13W	77*	6.0	6.6	20.	F	T	180, 40, -79/346, 51, -99	F
T9	10/11/75	14:35	24.91S	175.16W	11*	6.4	7.8	0.-35.	T	C	0, 29, 68/205, 63, 102	T
T10	4/02/77	07:15	16.79S	172.02W	33*	6.4	7.6	50.,5.-25.	G,T	C	170, 60, 85/ 0, 30, 99	T
T11	9/03/77	11:56	15.39S	173.07W	55	5.3	5.1	44.	HAR	T	122, 72, -82/277, 19,-113	HAR
T12	9/21/77	09:27	23.52S	175.18W	15	5.4	5.3	15.	HAR	T	98, 37, -45/226, 65,-119	HAR
T13	10/10/77	11:53	25.87S	175.37W	24*	6.4	7.2	20.,23.	EK,G	T	9, 35, -83/180, 55, -95	EK
T14	6/17/78	15:11	17.06S	172.28W	0	6.5	7.0	11.FIX,0.-20.	G,T	T	190, 60, -90/ 10, 30, -90	T
T15	11/13/79	20:43	23.61S	174.85W	32	6.4	6.6	10.FIX	G	T	22, 58, -76/177, 35,-111	G
T16	2/03/80	11:58	17.62S	171.16W	36*	5.9	6.4	33.	G	C	143, 42, 117/289, 53, 68	G
T17	12/15/80	08:12	17.59S	172.31W	30*	6.0	6.3	35.	G	C	212, 50, 119/351, 47, 60	G
T18	9/01/81	09:29	15.08S	173.12W	26*	6.5	7.5	20.FIX	DW83	T	115, 37, -73/273, 55,-103	DW83
T19	11/25/81	19:01	15.24S	173.26W	41*	5.6	5.8	22.	HAR	T	89, 73,-100/300, 20, -60	HAR
T20	2/28/82	17:00	21.65S	173.51W	38*	5.6	5.6	52.,42.	D83A,W	C	29, 30, 104/193, 61, 82	D83A
T21	6/02/82	12:37	18.11S	172.51W	70*	6.3	6.4	11.FIX	D83A	T	215, 55, -62/352, 44,-124	D83A
T22	5/11/83	21:48	21.42S	173.37W	32*	5.7	5.3	12.	D83C	C	71, 20, 130/210, 74, 77	D83C
T23	7/08/83	10:05	21.50S	173.37W	26	5.4	4.8	49.	D84A	C	73, 54, 145/185, 62, 41	D84A
T24	8/30/83	08:50	16.68S	172.05W	32*	5.9	5.6	40.	D84A	C	180, 54, 124/311, 48, 52	D84A
T25	3/22/84	14:13	15.23S	172.19W	42#	5.4	5.2	10.FIX	D84C	T	130, 50, -81/297, 41,-100	D84C
T26	6/29/84	04:28	20.93S	173.27W	42#	5.4	---	51.	D85A	C	229, 41, 149/344, 70, 53	D85A
T27	8/15/84	06:22	14.82S	173.53W	33#	5.2	---	45.	HAR	T	81, 73, -97/284, 19, -68	HAR
T28	10/19/84	01:28	14.84S	171.20W	33#	5.1	5.1	10.FIX	HAR	SS T	96, 87, 153/187, 63, 3	HAR
T29	6/21/85	04:31	28.44S	175.95W	47#	5.4	5.9	22.	PDE	T	28, 46, -56/163, 53,-121	PDE
T30	9/26/85	07:27	34.69S	178.66W	52#	6.3	7.0	61.	PDE	C	81, 60, 137/196, 54, 39	PDE
T31	3/14/86	16:55	30.07S	176.56W	42#	5.4	6.1	15.FIX	HAR	T	25, 43, -73/183, 49,-105	HAR

References are C, Cormier [1975]; CF, Chen and Forsyth [1978]; CI, Chinn and Isacks [1983]; CR85, Christensen and Ruff [1985]; C&F, Chapple and Forsyth [1979]; DW83, Dziewònski and Woodhouse [1983]; D83A, Dziewonski et al. [1983a]; D83B, Dziewonski et al. [1983b]; D83C, Dziewonski et al. [1983c]; D84A, Dziewonski et al. [1984a]; D84B, Dziewonski et al. [1984b]; D84C, Dziewonski et al. [1984c]; D85A, Dziewonski et al. [1985a]; D85B, Dziewonski et al. [1985b]; D85C, Dziewonski et al. [1985c]; EK, Eissler and Kanamori [1982]; F, Forsyth [1982]; F70, Fitch [1970]; F72, Fitch [1972]; FU81, Fujita et al. [1981]; G, Giardini et al. [1985]; HAR, Harvard catalog; HJ, House and Jacob [1983]; I81, Isacks et al. [1981]; JM, Johnson and Molnar [1972]; K71, Kanamori [1971a]; K72, Kanamori [1972]; KM, Korrat and Madariaga [1986]; KS, Katsumata and Sykes [1969]; NEIS, U.S. Geological Survey (USGS) moment tensor solution from Preliminary Determination of Epicenters (PDE) monthly listing; P78, Pascal et al. [1978]; P79, Pascal [1979]; PDE, Harvard catalog from PDE monthly listing (USGS); S68A, Stauder [1968a]; S68B, Stauder [1968b]; S72, Stauder [1972]; S73, Stauder [1973]; S75, Stauder [1975]; SB66, Stauder and Bollinger [1966]; SH, Shimazaki [1972]; SM, Stauder and Mualchin [1976]; T, this study; UB, Udias and Baumann [1969]; and W, Ward [1983]. Locations, depths, and magnitudes are from the ISC bulletin unless otherwise indicated (# indicates that hypocentral parameters are from PDE monthly bulletin). Tectonic class: T, tensional; C, compressional; SS, strike-slip.

* ISC depths were calculated using depth phase information.

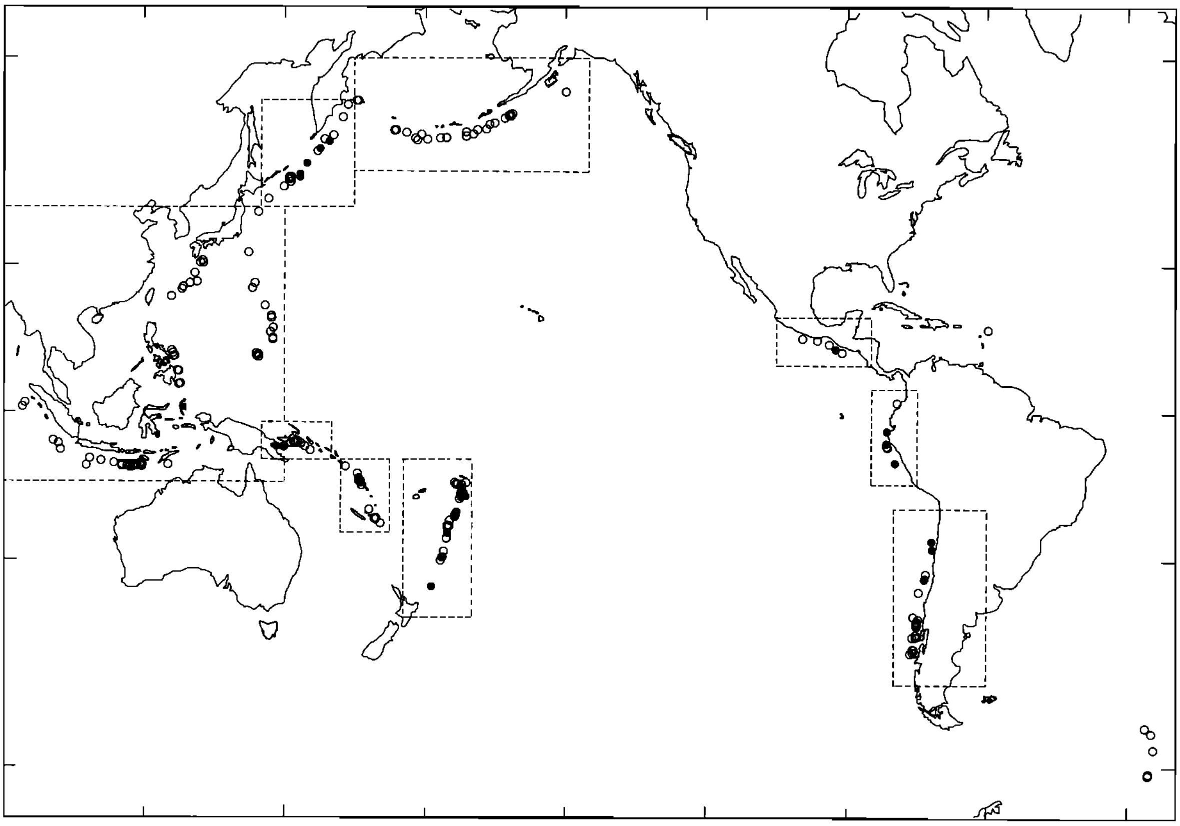

Fig. 2. Locations of all outer rise earthquakes listed in Table 3. Compressional and tensional events are plotted with solid and open symbols, respectively. The dashed boxes show the locations of the detailed maps in Figures 3-12.

Tensional Outer Rise Earthquakes

Tensional outer rise events have been observed in all of the major subduction zones. Our model suggests that tensional outer rise events occur in relatively uncoupled subduction zones in response to the continuous pull of the subducting slab and in coupled subduction zones following the incremental motions that occur during large underthrusting events. We find a full spectrum of occurrences of tensional outer rise events ranging from strongly coupled zones (e.g., Aleutians, Kuriles, South America), where nearly all of the tensional outer rise events can be related to the occurrences of underthrusting events, to uncoupled zones (e.g., Marianas, Java, Sumatra, Philippines, Ryukyu), where tensional outer rise events are uncorrelated with interplate seismicity. Subduction zones that have only tensional outer rise events which are apparently not correlated to interplate activity include Java, Sumatra, Marianas, Philippines, Izu Bonin, Ryukyu, Japan, Caribbean, and Scotia regions. In general, these zones correspond to zones in Table 2 with characteristic maximum earthquake sizes of 8.0 or less (i.e., relatively uncoupled zones). In contrast, for zones that have characteristic maximum earthquake sizes of 8.5 or greater, 93% of the tensional outer rise events follow, by 30 years or less, a large underthrusting event. Since many of the largest underthrusting events occurred less than 30 years ago, and most of the outer rise catalog follows these events, the significance of the above correlation may be questionable. There is, however, a conspicuous lack of tensional outer rise events which occur prior to the large underthrusting events during this same time period. The subduction zones with characteristic maximum earthquake sizes between 7.9 and 8.5 tend to show characteristics of both the coupled and uncoupled subduction zones. In these cases, large underthrusting events are often followed by tensional outer rise events; however, about half of the tensional outer rise events are apparently unrelated to interplate seismicity.

Compressional Outer Rise Earthquakes

Compressional outer rise earthquakes occur infrequently compared to tensional outer rise events by a ratio of about 1 to 6. The locations of compressional outer rise events are also more limited than those of tensional outer rise events and have only been found in zones that have characteristic maximum earthquake sizes of 7.9 or greater (intermediate and strongly coupled zones in Table 2). Our model suggests that compressional outer rise events occur adjacent to subduction zone segments that are locked and have a high seismic potential for large underthrusting events. Compressional stress accumulates in the outer rise, oceanward of locked portions of the interplate zone, from the continued motions in adjacent subducting segments.

There are 30 compressional outer rise events in Table 3. In four instances, compressional outer rise events have been followed by large underthrusting earthquakes (see regional studies below for South America and Tonga-Kermadec) as predicted by our model (see Table 1). The occurrences of these underthrusting events followed the associated compressional outer rise event by 2, 4, 7, and 19 years. At the time of our earlier paper [Christensen and Ruff, 1983] there was only one case in which a compressional outer rise event was known to have been followed by a large underthrusting event. The remaining compressional outer rise events are of interest because of their predictive value for large underthrusting events. Regions that have a high seismic potential (i.e., mature seismic gaps) can sometimes be recognized from the historic seismicity [e.g., Nishenko and McCann, 1981] but are often noted only after a large event has occurred. The occurrences of compressional outer rise events can be used as an additional indicator of the stress state in the interplate region. Regions which are of particular interest because of the occurrences of compressional outer rise events will be discussed in individual sections below and include segments of the Kurile Islands, Chile, Peru, Middle America, Tonga, Kermadec, New Hebrides, and the Solomon Islands. In each of these cases there is either a clear potential for a large underthrusting event based on the historical seismicity (i.e., seismic gap hypothesis) or an implied potential based on the proposed model.

Regional Studies

In the following sections we will review outer rise seismicity in various subduction zones and discuss individual correlations between outer rise seismicity and subduction seismicity. The "uncoupled" subduction zones, which appear to lack compressional outer rise events, will be discussed first, followed by the "coupled" subduction zones and the interesting occurrences of both compressional and tensional outer rise events in these regions. The events described in the following sections are listed in Table 3 chronologically by region.

Western Pacific, Atlantic, and Indian Ocean Regions (Uncoupled Subduction Zones)

This large region includes subduction zones in which only tensional outer rise events have been recorded and which have characteristic maximum earthquake sizes of 8.0 or less (i.e., intermediate and weakly coupled subduction zones). A total of 80 tensional outer rise events have been located in these subduction zones which includes the Java, Sumatra, Philippines, Marianas, Izu Bonin, Japan, Ryukyu, Caribbean, and Scotia regions. The Caribbean and Scotia subduction zones are not discussed in detail but behave in a manner similar to the uncoupled zones discussed in this section. The tensional outer rise events in Table 3 which occur in the western Pacific and Indian Ocean regions are shown in Figure 3. In these regions there seems to be no correlation between tensional outer rise events and inter-

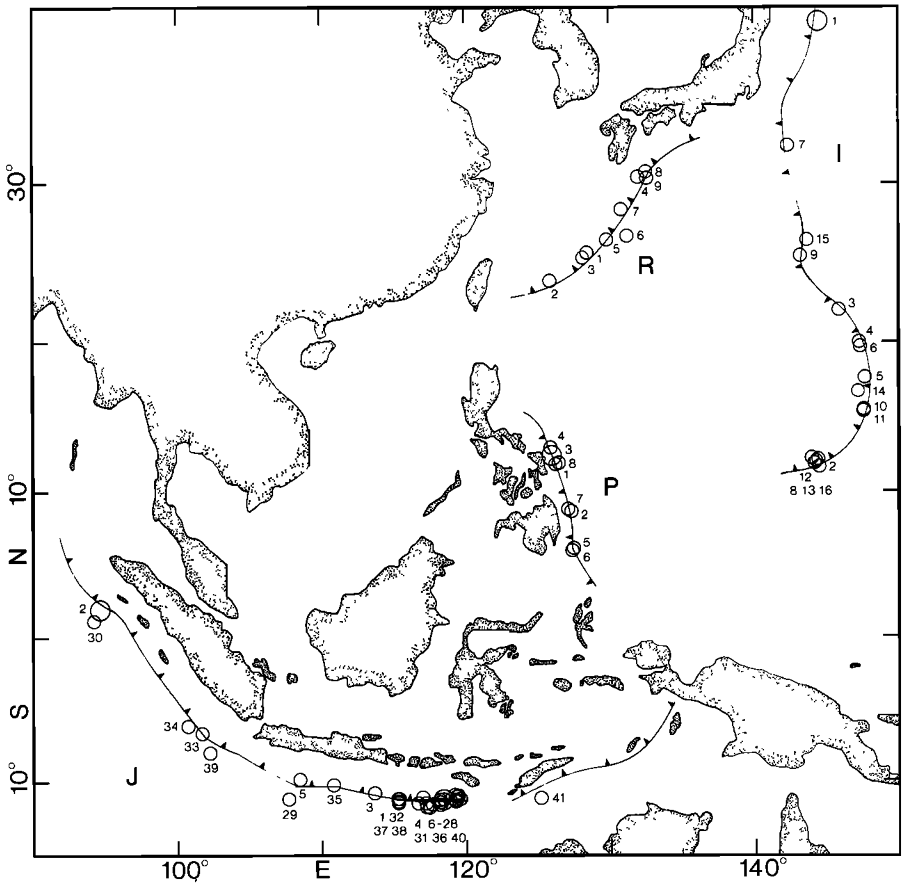

Fig. 3. Outer rise earthquakes associated with the relatively uncoupled subduction zones in the western Pacific and the Indian Ocean. All events shown are tensional outer rise events. The letter and number codes refer to the appropriate regions and events in Table 3 (e.g., J8 for Java-Sumatra region, event 8).

plate seismicity due to the almost complete lack of significant underthrusting events.

Extremely large tensional outer rise (or trench) events have occurred on rare occasions in these regions. These events can be as large as many large underthrusting events and may represent rupture through the entire lithosphere. Of particular interest are the 1933 Sanriku event ($M_W = 8.4$, I1) and the 1977 Sumba event ($M_S = 8.3$, J7) [see Kanamori, 1971a; Spence, 1986]. Large tensional outer rise events in other regions such as the March 7, 1929 (A1), and March 30, 1965 (A10), events in the Aleutians may be similar. The stresses needed to produce these large tensional outer rise events may be acquired through lateral variations in the interplate coupling of the zone. Unlike strongly coupled zones where tensional stress is transmitted to the outer rise after the occurrence of a large underthrusting event, in uncoupled subduction zones, tensional stress is continuously present in the outer rise. The effect of temporarily stopping or slowing down subduction in a segment of the subduction zone may be to increase the tensional stress in the adjoining segment of the subduction zone.

The 1933 Sanriku event is located along the northern Japan trench in a region that is in transition from a strongly coupled subduction zone to the north (i.e., Kurile Island Zone) to a weakly coupled zone to the south. This event is located in a trench segment south of the 1968 Tokachi-Oki underthrusting event; a region that was obviously strongly coupled prior to the 1968 event. A possible explanation for the occurrence of the 1933 Sanriku event is that the tensional stress from slab pull in this relatively uncoupled region was concentrated in the 1933 zone because of the stronger coupling in the northern (1968 Tokachi-Oki) segment [see Kawakatsu and Seno, 1983].

The 1977 Sumba event occurred in a trench segment which is abruptly truncated by the impingement of the Australian continental shelf on the eastern portion of the Sunda trench. In this case the Australian continent may serve as a barrier to subduction, while in the adjacent trench segment, subduction continues, resulting in the 1977 Sumba event [see Spence, 1986].

Solomon Islands Region

Most of the Solomon Islands subduction zone appears to have ruptured in the 1970s [Lay and Kanamori, 1980] in six underthrusting events with moment magnitudes between 7.3 and 8.1. Figure 4 shows the aftershock areas of these most recent underthrusting events, in addition to the outer rise events that have occurred in this region. The underthrusting sequence on July 14 and 26, 1971 ($M_w = 8.0, 8.1$), is followed by six tensional outer rise events occurring between 1971 and 1984, the two largest of which occurred on September 14, 1971 ($M_s = 6.3$, S3), and August 17, 1972 ($M_s = 7.1$, S4). The January 31, and February 1, 1974 ($M_w = 7.3, 7.4$), and the July 20, 1975 ($M_w = 7.7, 7.4$), underthrusting doublets were followed by one tensional outer rise event on May 1, 1977, in addition to a large strike-slip event in the vicinity of the trench which occurred on July 29, 1977 ($M_s = 7.2$, S8). A right-lateral sense of motion on the north-south trending nodal plane for the 1977 strike-slip event is consistent with the expected response of a north-south trending fracture to underthrusting motions in the Solomon plate. A small tensional outer rise event (S2) occurred on September 28, 1967, prior to the underthrusting activity in the 1970s. While it is unclear if this event followed an earlier sequence of underthrusting in the adjacent subduction zone, it does suggest that the adjacent

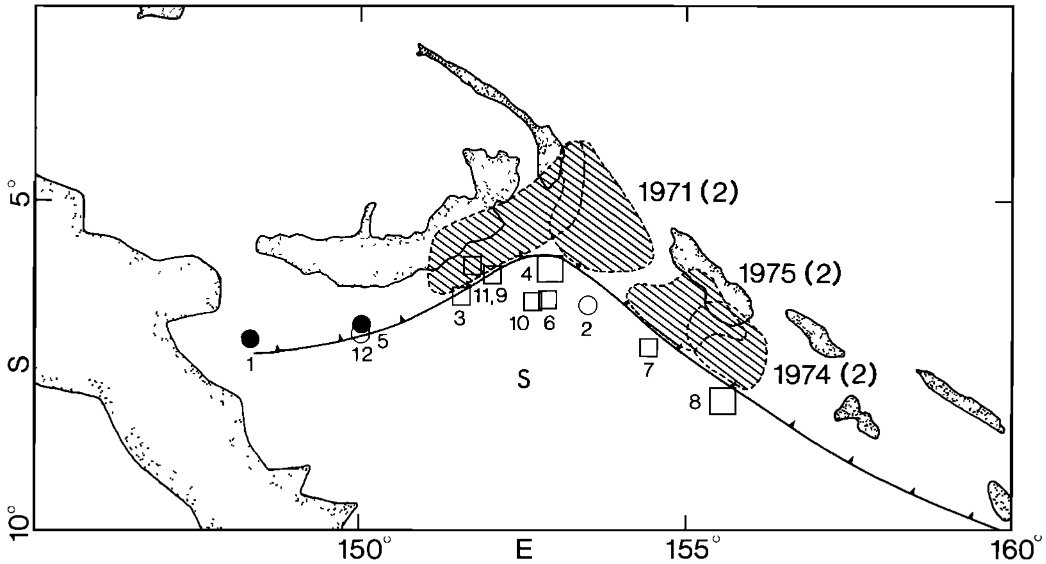

Fig. 4. Outer rise earthquakes in the Solomon Islands region. Tensional outer rise events are shown as the open symbols, and compressional outer rise events are shown as the solid symbols. Tensional events that follow a large underthrusting event by 30 years or less are displayed as open squares. Large outer rise events (M≥7.0) are shown by the larger symbols. The letter and number codes refer to the appropriate regions and events in Table 3. Significant underthrusting events are referred to by the year in which they occurred with their aftershock areas displayed as the hachured regions [after Lay and Kanamori, 1980]. Earthquake doublets are denoted by the numbers in parentheses.

subduction zone was not in compression, and thus it is interesting to note that this region is between the 1971 and 1975 doublets and does not appear to have ruptured during the recent underthrusting sequence. Two compressional outer rise events have been located in the New Britain region of the Solomon Islands. This segment of the arc did not rupture during the 1970s underthrusting sequence. The seismic history of this region suggests that it may have ruptured previously in a series of large events in 1945 and 1946 [Nishenko and McCann, 1981; Lay and Kanamori, 1980; McCann et al., 1979]. The first compressional outer rise event (S1) occurred in 1966 at the extreme western end of the Solomon trench, while the second (S5) occurred west of the 1971 underthrusting aftershock areas and followed the 1971 underthrusting events by less than 2 years. We suggest that this segment of the Solomon Islands trench is accumulating compressional stress and that the recent underthrusting activity in the Solomon Islands has added to the loading of the New Britain segment, thus causing additional compressional stress to accumulate. A recent tensional outer rise event (S12) on December 11, 1985, which occurred near the January 18, 1973, compressional outer rise event (S5), complicates this simple scenario and may suggest that the accumulated compressional stress has been dissipated by some mechanism such as aseismic slip in the subduction zone following the compressional outer rise event. The rare occurrence of compressional and tensional outer rise events in the same area (both spatially and temporally) can be explained in terms of the bending model [Chapple and Forsyth, 1979], and indeed the depths for these two events given in Table 3 support the bending stress explanation. While the bending model explains the similar locations and the depths of these events, we would still argue that the occurrence of compressional outer rise events requires a component of regional compression. We have already observed one case in the Kermadec region where a compressional outer rise event was followed by a tensional outer rise event adjacent to a region which subsequently ruptured in a large underthrusting event (see Tonga-Kermadec section). The complete lack of compressional outer rise events in uncoupled subduction zones and the strong correlation between compressional outer rise events and seismic gaps indicate that regional compression is necessary for their occurrence. In a later section of this paper we will discuss further the connection between plate bending and regional stress models.

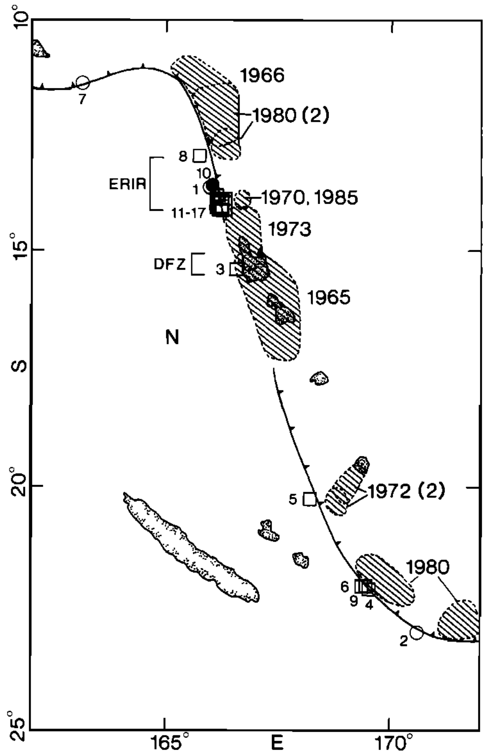

Fig. 5. Outer rise earthquakes in the New Hebrides region. The symbols are the same as those used in Figure 4. Aftershock areas of significant underthrusting events are adapted from Habermann [1984]. Locations of the East Rennell Island Ridge (ERIR) and the D'Entrecasteaux Fracture Zone (DFZ) are also shown.

New Hebrides Region

Sixteen tensional outer rise events have been identified in the New Hebrides region (see Figure 5). While six of these events follow large underthrusting events by 10 years or less, three seem to show no correlation. In this sense, the New Hebrides region exhibits characteristics of both coupled and uncoupled subduction zones. The remaining seven tensional outer rise events (N11-17) in November and December 1985 occurred in a very interesting earthquake sequence located north of the intersection of the D'Entrecasteaux Fracture Zone with the trench, in front of the East Rennell Island Ridge. In this series, two large tensional outer rise events ($M_S = 7.0$ and 7.1, N11 and N12) occurred about 1 hour apart and were followed by several aftershocks. These events are located directly trenchward of a moderate underthrusting event that occurred in 1970. The occurrence of tensional outer rise earthquakes following a moderate underthrusting event seems to conform to our model; however, the tensional outer rise events are followed on December 21, 1985, by a second moderate underthrusting event in the same region as the 1970 underthrusting event. The collision of the bathymetrically high East Rennell Island Ridge and D'Entrecasteaux Fracture Zone with the New Hebrides trench completely overrides the trench bathymetry from about 14°S to 17°S. The 1985 events occurred in the trench directly north of the collision zone. The geometry of these occurrences suggest that they are related to the impingement on the trench of the East Rennell Island Ridge to the south and the continued pull of the slab following subduction during the 1973 and 1970 events. The scenario is very similar to the 1977 Sumba scenario except it is the ridge system in this case which serves as a physical barrier to subduction while the tensional outer rise events help to detach the subducting slab from the barrier. After the tensional outer rise events have occurred, the slab is free to continue subducting an additional increment.

One compressional outer rise event (N10) which occurred on October 21, 1985, is located in the gap between the 1970/1985 and 1966/1980 events and suggests that this section of the trench is in compression, having been loaded by subduction to the north (in 1966 and 1980) and to the south (in 1970, 1973, and 1985). While the seismic history of this region is not well known, historic events have occurred in this general region and suggest that this gap may have the potential for large underthrusting events. Wyss et al. [1983] demonstrate that this region is experiencing a seismic quiescence which started in 1972 and suggest that this quiescence may indicate that the gap is in preparation for a future large underthrusting event (also see Habermann [1984]). A tensional outer rise event occurred in this same gap in 1964 (N1) prior to the surrounding subduction events, suggesting that the stress state of the outer rise has changed since that time from tensional to compressional following the subduction of segments to the north and south. The change from a tensional outer rise regime to a compressional outer rise regime, as the outer rise behind the locked segment of the interplate region is loaded by events in adjacent subduction segments, is an important step in the proposed model that has not been previously observed. The occurrence of a large underthrusting event in this segment of the subduction zone would complete the cycle and return the outer rise to a tensional regime and the start of a new cycle. A similar occurrence will be discussed in the Kurile Islands section.

South America (Chile) Region

This part of the South America subduction zone (20°S-45°S) serves as an excellent example of the various occurrences of outer rise events in a strongly coupled region. The subduction zone itself tends to release most of its accumulated stress in large or great underthrusting events [Kelleher, 1972; Kelleher et al., 1974], with the great May 22, 1960, Chilean event ($M_W = 9.5$) as the dominant feature. The aftershock areas of recent large underthrusting events located in this region are shown in Figure 6. The northern portion of the 1922 zone reruptured on October 4, 1983 ($M_S = 7.4$), and most of the 1906 zone has reruptured in two events; the first on July 9, 1971 [Malgrange et al., 1981], and the second on March 3, 1985 [Christensen and Ruff, 1986; Korrat and Madariaga, 1986]. Both tensional and compressional outer rise events have been located in this region. The 1960 Chilean event has been followed by 16 tensional outer rise events, five of which occurred within 9 years following the 1960 event [Stauder, 1973]. Tensional outer rise events occurring since 1977 with focal mechanisms reported by the Harvard group continue to occur oceanward of the 1960 Chilean event, demonstrating that this region has not had time to return to a compressional stress state.

There are three outer rise events located adjacent to the rupture area of the August 17, 1906 ($M_W = 8.2$), underthrusting event (see Figures 6 and 7). The first, which is a tensional outer rise event (C8) on September 25, 1971, occurred adjacent to and just 2 months after a large underthrusting event (July 9, 1971; $M_S = 7.5$) which ruptured the northern portion of the 1906 zone. The remaining two events (C11, C12) are compressional. The October 16, 1981, event (C11) is a large, shallow ($M_S = 7.2$) compressional outer rise event and is discussed in detail by Christensen and Ruff [1983, 1985]. The 1981 compressional outer rise event, as well as a smaller compressional outer rise event in 1982 (C12), occurred near the trench, just south of the aftershock zone of the 1971 underthrusting event. This region, which at the time of the 1981 compressional outer rise event was considered a seismic gap [Nishenko, 1985], has since reruptured in a large underthrusting event on March 3, 1985 ($M_S = 7.8$). We suggest that the occurrence of the 1971 underthrusting event triggered the tensional outer rise events in the adjacent trench region, in addition to loading the locked southern zone and adding an additional increment of compressional stress to the outer rise adjacent to the southern zone. The rupture of this southern zone in 1985 then completes the sequence.

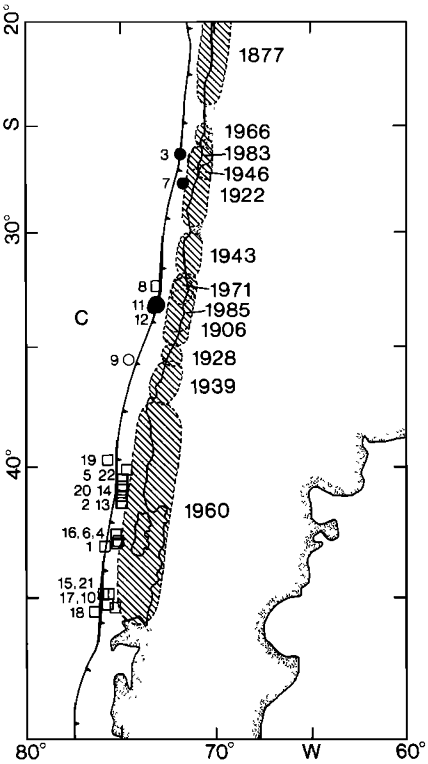

Fig. 6. Outer rise earthquakes in the South American subduction zone, Chile region. The symbols are the same as those used in Figure 4. Aftershock areas of significant underthrusting events are adapted from Kelleher [1972].

The remaining two compressional outer rise events in this region are located adjacent to the seismic gap associated with the November 11, 1922 ($M_W = 8.5$), underthrusting event. The compressional outer rise event (C3) of August 18, 1964, is located in the northern portion of the 1922 zone and was followed by a moderate sized underthrusting event on October 4, 1983 ($M_S = 7.4$). The compressional outer rise event (C7) on November 13, 1969, is located near the southern half of the 1922 aftershock zone and indicates that compressional stress is accumulating in this portion of the subduction zone. It should be noted that although the focal mechanism listed for this event in Table 3 is mostly strike slip, the compressional axis is more or less perpendicular to the trench and thus can be considered compressional by our criterion, although the possibility exists that this event is controlled by tensional stresses subparallel to the trench. Chapple and Forsyth [1979] also considered this event to be a compressional outer rise event.

Thus, in the Chile region there are two cases where compressional outer rise events have been followed by large underthrusting events as the model would predict and one additional compressional event which may point to some future occurrence.

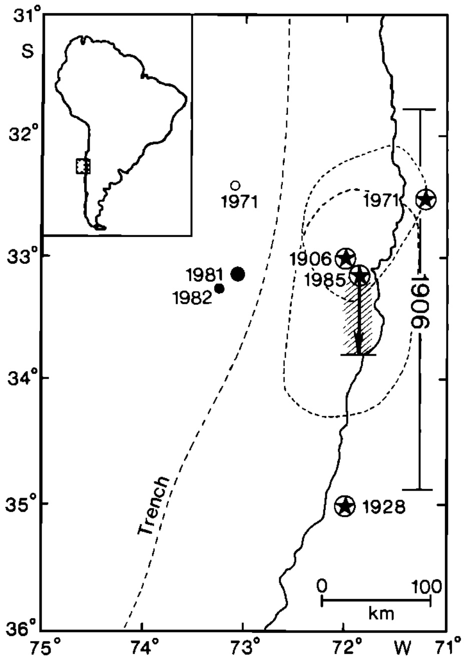

Fig. 7. Blowup of the central Chile region (adapted from Nishenko [1985]) showing outer rise earthquakes associated with the 1906 rupture zone and recent underthrusting events in 1971 and 1985. The epicenters of large and great ($M_S \geq 7.5$) underthrusting events are shown as the large circled stars, and the rupture extent of the great 1906 event is outlined by the vertical bar on the right. The aftershock areas of the 1971 and 1985 underthrusting events are enclosed by the dashed lines. The hachured area represents the asperity which ruptured in the 1985 event [see Christensen and Ruff, 1986]. One tensional outer rise event (1971) and two compressional outer rise events (1981, 1982) are shown by the open and solid symbols, respectively.

South America (Ecuador, Peru and Colombia) Region

The sequence of events in the Ecuador-Peru region is particularly interesting, though more difficult to interpret. The Ecuador-Peru region can be divided into two segments separated by the Mendana fracture zone which intersects the trench at the 1970 rupture zone (see Figure 8). The southern segment between 10° and 15°S is characterized by the occurrence of large underthrusting events, including the most recent, from north to south, in 1966, 1940, and 1974 [Kelleher, 1972; Dewey and Spence, 1979; Beck and Ruff, 1986; Abe, 1972b]. The northern segment between 0° and 10°S, which we will refer to as the Peru Quiet Zone, has no known history of large underthrusting events. Three compressional outer rise events (E3,E5,E6) have occurred in the Peru Quiet Zone since 1967 (see Figure 8). These events suggest that compressional stress has accumulated in the outer rise of this region. This interpretation might suggest that the seismic potential of this region is high, even though there is no history of large subduction events. On the other hand, two tensional outer rise events (E1,E2) have also occurred in the same region and may suggest that compressional stress is not accumulating in the outer rise of the Peru Quiet Zone. The fact that both tensional events occurred prior to the three compressional outer rise events could suggest that we have observed a change in the stress state from tension to compression in the outer rise adjacent to the Peru Quiet Zone. It is interesting to note that the three compressional outer rise events occurred after the large October 17, 1966 ($M_W = 8.1$), underthrusting event (see Figure 8) located just south of the Peru Quiet Zone and that this event may have led to the loading of the adjacent northern segment. We must remember, however, that the Peru Quiet Zone is over 1000 km long and that outer rise events in this region may be reflecting several different stress states within the zone. Nevertheless, it appears that the compressional outer rise event (E3) on September 3, 1967, which is located just north of the 1966 aftershock zone, occurred in response to the loading of the northern region after the 1966 events.

The story is further complicated by the occurrence of a large intermediate depth intraplate event on May 31, 1970 ($M_S = 7.6$; ISC depth = 48 km) [Abe, 1972b]. This normal (tensional) event occurred at the downdip edge of the coupled zone in the downgoing plate and straddles the boundary between the Peru Quiet Zone to the north and the normal underthrusting zone to the south. Although the 1970 event is not an outer rise earthquake, it is of interest in this paper because of its possible connection to interplate coupling. The combination of the compressional outer rise event (E3) oceanward of the interplate coupled zone and the tensional event at the downdip edge of the coupled zone may indicate that the interplate region is strongly coupled and accumulating compres-

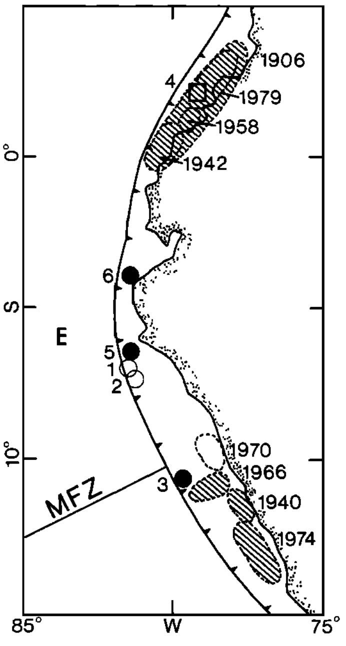

Fig. 8. Outer rise earthquakes in the Ecuador, Peru, and Colombia subduction zones of South America. The symbols are the same as those used in Figure 4. The 1970 event which is displayed with its aftershock zone is not an underthrusting event, but a large normal intraplate event which occurred at the downdip edge of the interplate coupled zone. Aftershock areas of significant underthrusting events are adapted from Kelleher [1972] and Kanamori and McNally [1982]. The Mendana Fracture Zone (MFZ) is also shown.

sional stress through motion in the adjacent southern segment, with the 1966 underthrusting event adding the additional stress that resulted in both of these intraplate events. Unlike the uncoupled subduction zones where slab pull forces are transmitted directly to the outer rise, in the strongly coupled zones, tensional stress from slab pull may accumulate at the downdip edge of the coupled region and can only be transmitted to the outer rise in small increments following large underthrusting events. The 1970 event may have resulted through a combination of the strong coupling in the Peru Quiet Zone to the north and trenchward of the 1970 event and the continued incremental motions of the underthrusting events to the south. This may have concentrated the stresses needed to cause the 1970 event at the downdip edge of the coupled zone. Alternatively, unbending of the subducting slab has been suggested as a possible explanation for the 1970 event [see Isacks and Barazangi, 1977]. Recent studies of the May 31, 1970, event indicate the possibility of a complicated rupture process [see Dewey and Spence, 1979; Beck and Ruff, 1988]; however, it is unclear how this complication effects the coupling story.

Given the complexities that exist in this region, we hesitate to over idealize the situation. However, we suggest that the more recent occurrence of compressional outer rise events in the Peru Quiet Zone reflects an accumulation of compressional stress in the region. The subduction segment directly north of the 1966 aftershock zone and updip of the 1970 tensional event appear to be strongly coupled and may have a high potential for a large underthrusting event.

Large earthquakes in the Colombia subduction zone (0°-5°N) in 1942, 1958, and 1979 [see Beck and Ruff, 1984; Kanamori and McNally, 1982] have completely reruptured the trench segment associated with the earlier 1906 earthquake (see Figure 8). In this zone there is one tensional outer rise event (E4) on January 2, 1981, which followed the December 12, 1979 ($M_W = 8.2$), Colombian underthrusting event.

Middle American Region

This region which includes Mexico and part of Central America can be characterized by the occurrence of many intermediate size underthrusting events with small rupture lengths and relatively short recurrence times [McNally and Minster, 1981]. Because of this tendency, it is difficult to associate directly outer rise seismicity to any single underthrusting event. In this region, tensional outer rise events have been observed to follow underthrusting events. However, in some cases, it may be necessary for two or more adjacent zones to rupture before the tensional stress can be effectively transmitted to the outer rise due to the small rupture areas. Figure 9 shows outer rise events that have occurred in the region along with the major subduction zone aftershock regions. One tensional outer rise event (M1) occurred in 1970 just 2 years after the 1968 underthrusting event but is located adjacent to underthrusting events in 1950 and 1957; one event in 1972 (M3) follows the 1965 underthrusting event, and one in 1981 (M4) follows the 1970 underthrusting event. The last tensional outer rise event (M5) can not be related to interplate seismicity. A compressional outer rise event (M2) occurred in the region on August 20, 1971, trenchward of underthrusting events which occurred in 1942 and/or 1950. The short recurrence times for events in this region of about 30 years [McNally and Minster, 1981] may suggest that the 1942 and 1950 zones have returned to a compressional stress state.

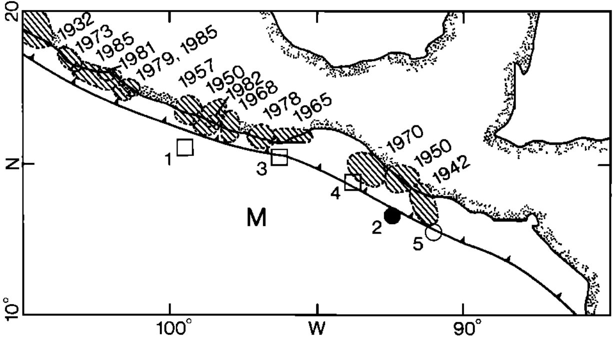

Fig. 9. Outer rise earthquakes in the Middle America subduction zone. The symbols are the same as those used in Figure 4. Aftershock areas of significant underthrusting events are adapted from Kelleher et al. [1973], Tajima and McNally [1983], and Eissler et al. [1986].

Aleutian–Alaska Arc Region

The Aleutian-Alaska arc is a good example of a strongly coupled subduction zone. Three of the largest events of this century have occurred in this region (April 9, 1957, Aleutian, $M_W = 9.1$; March 28, 1964, Alaskan, $M_W = 9.2$; February 4, 1965, Rat Islands, $M_W = 8.7$). There are 24 tensional outer rise events in the region, 21 of which follow the great underthrusting events mentioned above. The 1957 Aleutian event is followed by 14 events, five of which may be more closely associated with the 1946 event at the extreme eastern extension of the 1957 aftershock zone. The 1964 Alaska event was followed by one and the 1965 Rat Islands event by six tensional outer rise events [e.g., Stauder, 1968a,b; Spence, 1977]. Of the remaining three events, two (A9,A21) are located in the far western portion of the arc, near the Kamchatka peninsula, yet one of these (A9) occurred only 4 days after the 1965 Rat Islands event, and the other (A1) occurred in 1929 following an earlier sequence of underthrusting events in the early 1900s. The two events (A9,A21) which are located at the intersection of the Aleutian and Kurile Islands trenches, near the Komandorsky Islands, may be related to a more complicated tectonic regime [see Newberry et al., 1986]. The locations of the outer rise events along with the aftershock areas of the recent great underthrusting events are shown in Figure 10. No compressional outer rise events have been reported in the Aleutian-Alaska arc. Since this zone is the source of some of the largest known underthrusting events, we expect that compressional outer rise events may have occurred prior to these events. The lack of such events may simply be due to the poor station coverage that existed prior to 1962 (pre-World-Wide Standard Seismograph Network (WWSSN)) and thus the occurrence of small outer rise events in the time period before the major underthrusting events would be unnoticed.

Kurile Islands and Kamchatka Region

The Kurile Islands and Kamchatka region is centered on a 500-km-long segment known as the Kurile Islands trench gap. This segment has no known his-

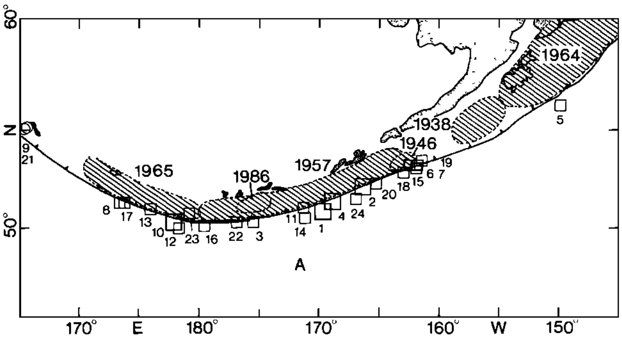

Fig. 10. Outer rise earthquakes in the Alaska-Aleutian arc. The symbols are the same as those used in Figure 4. Aftershock areas of significant underthrusting events are adapted from Sykes [1971].

torical occurrence of large underthrusting events, and thus its seismic potential is unknown [Kelleher et al., 1974]. An event in 1915 may have ruptured a portion of this region; however, it is not known if this event represents interplate thrusting [McCann et al., 1979; Lay et al., 1982]. The trench segment is flanked by the aftershock areas of the January 4, 1952 ($M_w=9.0$), Kamchatka event to the northeast and the October 13, 1963 ($M_w=8.5$), Kurile Islands event to the southwest (see Figure 11). Other aftershock zones of large underthrusting events in the region are also shown in Figure 11. The 1952 Kamchatka event and the 1963 Kurile Islands event were followed by three and five tensional outer rise events, respectively, adjacent to their aftershock regions in the following 30 years. Tensional outer rise events also occurred following the 1952 Hokkaido and 1959 Kamchatka events. More interestingly, five compressional outer rise events have occurred in the region since 1963. Three of these events occurred in the Kurile Islands trench gap. The largest event (K2) on March 16, 1963 ($m_b=7.7$), is studied in the appendix. The occurrence of compressional outer rise events in the gap suggests that the Kurile Islands trench gap has a high seismic potential, a suggestion not confirmed by historical seismicity. In the last 5 years, two compressional outer rise events (K11,K16) have occurred directly north of the Kurile trench gap and seem to suggest a northern extension of the compressional outer rise regime into the southern section of the 1952 Kamchatka rupture area. If this is the case, we have observed the change through time in the southern 1952 Kamchatka rupture area from a tensional outer rise regime following the 1952 Kamchatka underthrusting event to a compressional regime as the continued loading of the gap starts to reload the southern section of the 1952 region. Thus three stages in the cycle are recorded in this region, requiring only the occurrence of the next large underthrusting event to complete the circuit and start the next cycle. The Kurile Islands trench gap is at least 500 km long (about the same size as the region which ruptured in the 1952 underthrusting event) and has consistently produced compressional outer rise events since being loaded by the occurrence of the 1952 and 1963 underthrusting events. We suggest that the potential for a large underthrusting event in this region is high.

Tonga-Kermadec Islands Region

The Tonga-Kermadec Islands region is unusual because of the large number of outer rise events that occur there, 31 in all including 14 compressional outer rise events (see Figure 12). Half of the outer rise events in this region occur in the northern corner of the Tonga trench (15°-18°S). Both tensional and compressional events occur in the northern corner but cannot be related to subduction zone dynamics in a simple way. The stresses in this region may be controlled by the unusual corner geometry and thus hard to relate to our model.

Tensional outer rise events in the Tonga-Kermadec region do not seem to be associated with the interplate seismicity and generally behave like tensional outer rise events in uncoupled zones. There are seven compressional outer rise events in the remainder of the Tonga-Kermadec region (excluding the northern corner), and in two cases a compressional outer rise event has been followed by a large underthrusting event in the adjacent subduction zone. The July 2, 1974 ($M_s=7.2$), outer rise event (T7) was followed by a large underthrusting doublet event in northern Kermadec (January 14, 1976; $M_s=7.7,8.0$), and the October 11, 1975 ($M_s=7.8$), outer rise event (T9) was followed by a large underthrusting event on December 19, 1982 ($M_s=7.7$). The last five compressional outer rise events occur in two distinct regions. One compressional outer rise event which occurred in 1985 (T30) is located in southern Kermadec (≈35°S), and four compressional outer rise events the earliest of which occurred in 1982 (T20,T22,T23,T26) are located in central Tonga (≈21°S). The seismic potential of these two regions is unknown because of a lack of historic seismicity, although Wyss and Habermann [1984] have described the central Tonga region (≈21°S) as the most active in the Tonga-Kermadec arc. Our results suggest that compressional stress is accumulating in the outer rise and in the adjacent subduction zone and that the potential for a future large underthrusting event is high in these two regions.

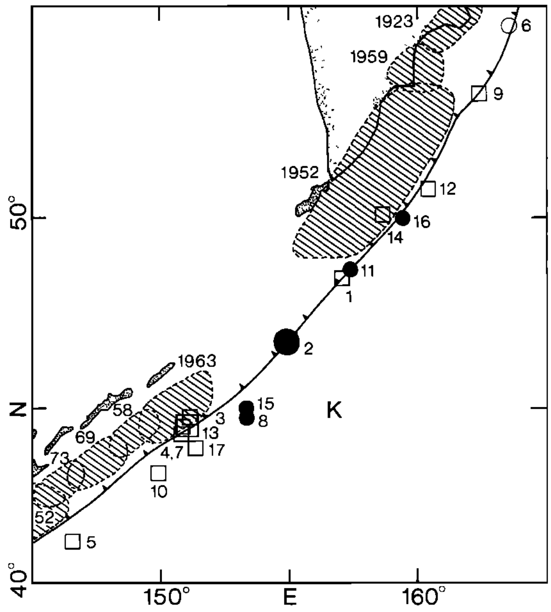

Fig. 11. Outer rise earthquakes in the Kamchatka-Kuriles region. The symbols are the same as those used in Figure 4. Aftershock areas of significant underthrusting events are adapted from Kelleher et al. [1973] and Schwartz and Ruff [1987].

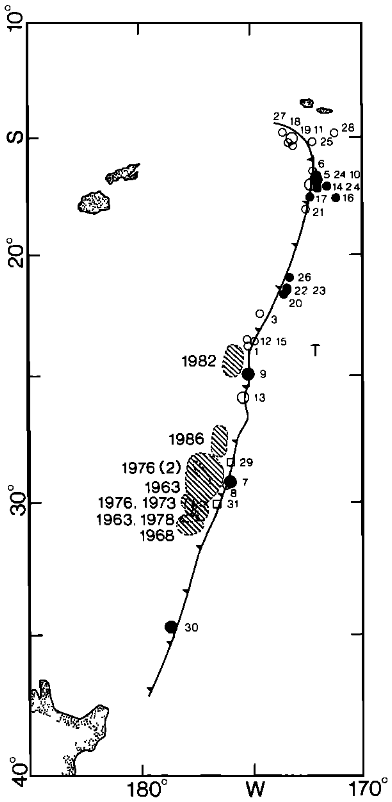

Fig. 12. Outer rise earthquakes in the Tonga-Kermadec subduction zone. The symbols are the same as those used in Figure 4. Aftershock areas of significant underthrusting events are adapted from Wyss and Habermann [1984].

Summary of Regional Studies

Detailed observations of outer rise seismicity tend to support the proposed relationship between outer rise events and the regional stress regime due to the interplate coupling of the major subduction zones. The complete lack of compressional outer rise events in "uncoupled" subduction zones (i.e., those zones with maximum characteristic size of <7.9) suggests that tensional stresses from plate bending and/or slab pull dominates in these regions. In the strongly coupled subduction zones, tensional stresses are only transmitted to the outer rise following a large underthrusting earthquake. Although tensional outer rise events are 6 times more common than compressional outer rise events, there are, with two minor exceptions, no tensional events which occur before (less than 28 years) and directly oceanward of a large underthrusting event. The two exceptions occurred in the intermediate coupled zones. In the first case a tensional outer rise event occurred 1 day after a large compressional outer rise event in the Kermadec region, apparently as one of the aftershocks. This zone later ruptured in the January 14, 1976 (M_S=7.7, 8.0), underthrusting doublet events. The second exception occurred in northern New Hebrides and is explained in the above regional section. There are no exceptions in the strongly coupled zones. Compressional outer rise events occur in more strongly coupled regions and tend to be located in "seismic gaps" (as observed from hindsight or from historical seismicity studies).

In four instances, compressional outer rise events have been followed by large underthrusting events. Underthrusting events in the Tonga-Kermadec region on January 14, 1976, and December 19, 1982, and in the Chile region on October 4, 1983, and March 3, 1985, followed compressional outer rise events by 2, 7, 19, and 4 years, respectively. The remaining 25 compressional outer rise events occur in nine distinct regions in which compressional stress may be accumulating in both the outer rise and the interplate coupled zone. The earliest compressional outer rise event, which is in our catalog and has not yet been followed by a large interplate thrusting event, occurred in the Kurile Islands in 1963, approximately 24 years ago.

It should be understood that the lack of outer rise seismicity does not necessarily indicate a lack of stress accumulation in the interplate zone. Indeed, many large underthrusting events have occurred with no associated outer rise seismicity recorded either before or after the events. We would expect that the occurrence of outer rise events depends not only on the regional stress accumulation but also on the existence and orientation of preexisting zones of weakness (or faults) and also on other mechanical properties of the plate (e.g., age, thickness, velocity, etc.).

Depth Considerations

Outer rise earthquakes have traditionally been viewed as a direct result of plate bending [e.g., Stauder, 1968a,b; Chapple and Forsyth, 1979]. The plate bending model predicts that compressional outer rise events should occur at deeper depths than tensional outer rise events. Thus far in this paper we have not dealt with the depth variations found in outer rise events, nor does the regional stress model that we propose directly address the effects of bending forces. In Table 4 we have compiled a list of outer rise events with well-determined depths from several sources including our own investigation of the depth distributions of some of the larger events which are described in the appendix. This list includes the depths of 33 outer rise events, 23 tensional and 10 compressional. We have included only events in which the depths were determined from detailed studies using depth phase information and/or waveform modeling. In Figure 13 the depths from Table 4 are plotted for the tensional and compressional outer rise events. While tensional outer rise events seem to be limited to depths of 25 km or less, the compressional outer rise events extend down to about 50 km. The upper extent of rupture for the larger compressional outer rise events studied in the appendix is not well determined; however, it seems probable that some of these events, because of their large size and expected rupture area, may have ruptured to the surface. Although the scatter in the hypocentral depths is fairly large, it is clear that the compressional outer rise events tend to occur at deeper depths, or at least occur over a greater depth extent, than the tensional outer rise events (also see Chapple and Forsyth [1979], Ward [1983], and Eguchi et al. [1987]). In Table 4 we have not included depth estimates for some of the largest known outer rise events. While large tensional outer rise earthquakes such as the 1933 Sanriku and the 1977 Sumba events may have ruptured through the entire lithosphere, their depth extent is still somewhat controversial. In Figure 13 we have plotted the possible depth extent of the 1977

TABLE 4. Depths of Outer Rise Earthquakes

No.	Date	Magnitude Mb	Magnitude Ms	Depth Estimate km	References	Tectonic Class T/C
K2	Mar. 16, 1963	7.7	---	10.-50.	T	C
N1	Jan. 22, 1964	6.3	---	21.	CI	T
K4	Apr. 5, 1965	5.6	---	25.	F	T
A13	Jun. 2, 1966	5.9	---	23.	FU81	T
N2	Sep. 12, 1966	5.9	---	18.,17.	CI,P78	T
T2	Nov. 12, 1967	5.6	---	42.	CF	C
A15	Jun. 20, 1969	5.8	5.1	14.	HJ	T
J2	Nov. 21, 1969	6.4	7.7	0.-20.	T	T
M2	Aug. 20, 1971	5.8	5.6	19.	C&F	C
K7	Sep. 9, 1971	6.0	5.9	15.	F	T
J3	May 4, 1972	5.8	---	10.	F	T
T5	Aug. 7, 1972	5.8	6.0	45.	F	C
S4	Aug. 17, 1972	6.3	7.1	0.-6.	T	T
T6	Sep. 27, 1972	5.8	6.0	6.	CF	T
A18	Oct. 13, 1972	6.0	5.4	10.	HJ	T
T7	Jul. 2, 1974	6.5	7.2	5.-30.	T	C
T8	Jul. 3, 1974	6.0	6.6	20.	F	T
I7	Aug. 25, 1974	5.9	5.6	6.	F	T
A19	Aug. 2, 1975	6.0	6.0	15.	HJ	T
T9	Oct. 11, 1975	6.4	7.8	0.-35.	T	C
T10	Apr. 2, 1977	6.4	7.6	5.-25.	T	C
S8	Jul. 29, 1977	6.3	7.2	0.-15.	T	SS
T13	Oct. 10, 1977	6.4	7.2	20.	EK	T
T14	Jun. 17, 1978	6.5	7.0	0.-20.	T	T
K9	Feb. 1, 1981	5.9	5.5	12-20	W	T
K10	Apr. 30, 1981	6.1	6.2	6-12	W	T
P5	May 26, 1981	5.7	5.2	10-24	W	T
A20	Jun. 5, 1981	5.6	4.2	6-10	W	T
K11	Aug. 23, 1981	6.0	5.8	36-42	W	C
K12	Oct. 1, 1981	5.9	6.1	6-12	W	T
C11	Oct. 16, 1981	6.2	7.2	0-20,12-24	CR85,W	C
T20	Feb. 28, 1982	5.6	5.6	42.	W	C
J31	Feb. 28, 1982	5.6	---	6-12	W	T

References are the same as in Table 3.

Sumba event. While it is generally accepted that this event ruptured to the surface, estimates for the lower depth extent range from about 25 km [see Fitch et al., 1981] up to 90 km [see Given and Kanamori, 1980].

The overlap between the depths of tensional and compressional outer rise events may be explained as scatter in the data due to the inability to resolve the true depth, particularly the upper depth extent of the larger events. However, we suggest that these variations are real and in fact are expected due to the combined effects of regional and plate bending stresses. Ward [1984] shows calculations for the position of the neutral surface in an elastically bending plate with the application of regional stresses. Ward's results suggest that the neutral surface can be raised or lowered as much as 20 km by the addition of regional compression and tension, respectively. This suggests that in extreme cases it may be possible to raise the neutral surface out of the plate, putting the entire plate in a compressional regime such as in the case of the shallow 1981 Chile outer rise event [Christensen and Ruff, 1983, 1985], or to lower the neutral plane enough to put the entire plate in tension such as in the 1933 Sanriku event [Kanamori, 1971a].

The large number of tensional outer rise events which occur in all coupling situations suggests that the normal behavior of the outer rise is to fail in a shallow tensional mode, controlled by bending stresses in addition to the regional tensional stresses from slab pull [see Spence, 1987]. This tensional mode of deformation at the top of the plate in the outer rise is also manifested in the horst and graben structure that is sometimes observed in the bathymetry and seismic profiling [Hilde, 1983]. The addition of regional tension would be necessary for the larger tensional (Sanriku type) events that may have ruptured through the entire lithosphere. The simple observation that compressional outer rise events are limited to more strongly coupled regions suggests that the addition of a regional compressive stress is required for the occurrence of compressional outer rise events. The effects of regional compression may be to elevate the compressional regime of the plate bending scheme into a brittle region and in extreme cases to extend it to the surface.

Conclusions

Our model predicts that the occurrence of outer rise events varies both spatially and temporally. While spatial variations have been thoroughly discussed, the temporal variations remain untested. Only in the Kurile Islands and New Hebrides regions do we see a change in the stress state in the outer rise from tensional to compressional with time. These predictions can be tested in the future as more earthquake cycles are observed.

The proposed model does not require the presence of stress from plate bending to explain the spatial and temporal distribution of outer rise events. However, as has been noted in several studies [e.g., Chapple and Forsyth, 1979; Ward, 1983; Eguchi et al., 1987; Dmowska and Lovison, 1988; Dmowska et al., 1988], the depths of these events are consistent with the plate bending model with the addition of regional stresses. For the simplest case of the regional stress model (i.e., no bending stresses) it would be

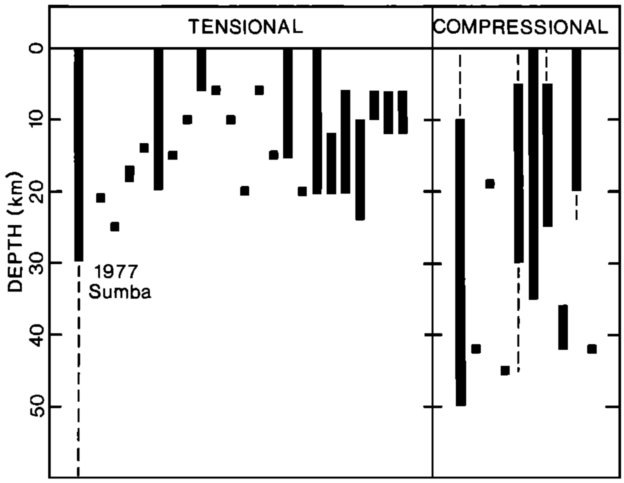

Fig. 13. Depths of outer rise events listed in Table 4. Tensional outer rise events are shown on the left, and compressional outer rise events are shown on the right. Depths are plotted in chronological order from left to right, except for the 1977 Sumba event which is not listed in Table 4. Vertical bars mark the probable depth distribution for the larger outer rise events. Dashed lines represent possible extensions of the depth distribution.

necessary for the stress state of the outer rise to vary from a compressional regime to a tensional regime during the course of a single large underthrusting event. However, if we account for bending stresses in addition to the regional stresses, we could explain the change from compressional to tensional outer rise seismicity simply by decreasing the regional compressive stress through a large underthrusting event. As suggested by Ward [1984], this could move the neutral surface to deeper depths and produce a near-surface tensional regime even though the regional stress could still be slightly compressive. In uncoupled subduction zones the continuous pull of the subducted slab in addition to the bending stresses would produce the shallow tensional events that we observe there. The combination of regional and bending forces seems the simplest and most reasonable way to explain the observed behavior of outer rise seismicity.

The effect of coupling on the regional stress field is also evident in the overriding plate and in the subducting plate below the interplate coupled zone [e.g., Astiz and Kanamori, 1986; Spence, 1977, 1986, 1987; McNally et al., 1986; Dewey and Spence, 1979; Seno, 1979; Dmowska and Lovison, 1988; Dmowska et al., 1988; Lay et al., 1988]. Whereas the outer rise seismicity can be readily studied due to the easy identification of events, other intraplate seismicity must first be isolated from the interplate activity, and separated into events in the overriding or subducting plate. This separation requires very good depth resolution and is a much harder problem. Further studies of these other environments in the future should prove to be both interesting and important in predicting large underthrusting events.

Detailed observations of outer rise earthquakes confirm that these events can be directly related to processes which occur in the interplate regions. The coupled or uncoupled nature of the subduction zone [Lay et al., 1982; Uyeda and Kanamori, 1979; Ruff and Kanamori, 1980] along with the semiperiodic effects related to the earthquake cycle produce regional stresses that strongly influence the seismic behavior of the outer rise. While in strongly coupled regions we have found that tensional outer rise events nearly always follow large underthrusting events, in intermediately coupled regions they may also occur uncorrelated to subduction seismicity. Compressional stress, on the other hand, accumulates oceanward of regions that are strongly coupled and have not recently ruptured (i.e., seismic gaps). Compressional stress accumulates in these regions due to the continued slip in bordering subduction zone segments. Compressional outer rise events are observed both prior to large underthrusting events and in zones that are assumed to have a high seismic potential for some future large event based on the historic seismicity (i.e., known seismic gaps). Compressional outer rise events also occur in regions where the seismic potential is unknown due to a lack of seismic history. Our model suggest that these regions are accumulating compressional stress both in the outer rise and in the interplate region and may also have a high seismic potential. Subduction zone segments in which compressional outer rise events have occurred are shown in Figure 14. The four stars in Figure 14 mark the regions where large underthrusting events have followed compressional outer rise events (i.e., successful predictions of the model). The remaining nine regions in Figure 14 may have a high potential

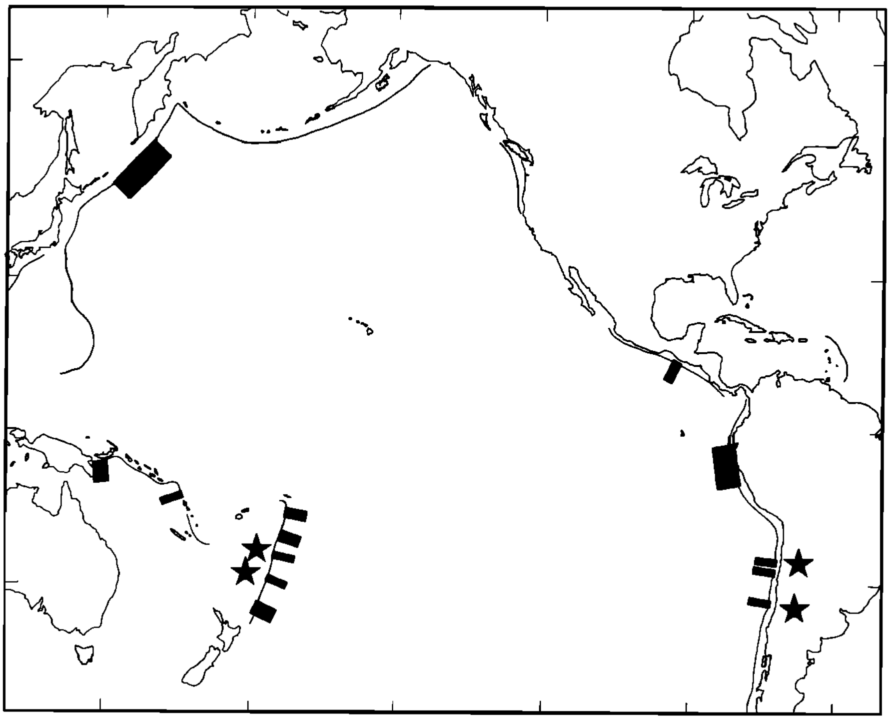

Fig. 14. Distribution of compressional outer rise earthquakes around the circumpacific. Regions where compressional outer rise events have occurred are shown by the heavy bars. Segments in which the compressional outer rise events have been followed by a large underthrusting event in the adjacent interplate region are marked by stars.

for a large underthrusting event in the near future based on our model.

Appendix: Focal Mechanisms and Depths of Large Outer Rise Events

Detailed analyses of the nine large (M≥7.0) outer rise events listed in Table A1 are included in this appendix. Lower hemisphere equal-area focal mechanisms for six of these events determined in this study are shown in Figure A1 and focal parameters are listed in Table A1. The nodal planes are constrained by P wave first motions with solid circles representing compressional arrivals and open circles representing dilatational arrivals. In most cases only the steeper nodal plane is well determined from the first motion data. For the event on October 31, 1975, neither nodal plane is well constrained, and although the focal mechanism is obviously tensional, further modeling to obtain the depth extent was not attempted. In three cases the focal mechanisms were taken from previous studies (see references in Table A1).

In order to determine the depth extent of each event in Table A1 we have utilized the method outlined by Christensen and Ruff [1985]. This method consists of deconvolving source time functions from the observed seismograms [see Ruff and Kanamori, 1983a] using a range of point source depths. These source time functions for the compressional outer rise events are then evaluated for "simplicity" using the statistical parameters $T_{1/2}$ which is described by Christensen and Ruff [1985]. The results are plotted on $T_{1/2}$ versus depth curves in Figure A2 and the best depth extent determined by the range of low $T_{1/2}$ values. The resulting depth distributions for the compressional outer rise events are shown by the vertical bars in Figure A2 and listed in Table A1 and Table 4. While the lower depth extent of faulting is well determined using this method, the shallow extension of the fault is not well defined. The tensional outer rise events all tend to be very shallow and thus, as discussed by Christensen and Ruff [1985] the simplicity parameter ($T_{1/2}$) is not stable. This instability originates from two effects. The first is a loss of depth information recorded in the long-period frequency band for shallow events (a direct result of the short time delays for the depth phases), and the second is a similar effect which occurs as the delay times for the depth phases become shorter than the duration of the source time function. In addition, shallow earthquakes occurring below the ocean floor tend to produce sizable reverberations in the water column which are not easily accounted for using standard methods [see Wiens, 1987]. These factors present problems for determining depths of shallow events. Thus we have chosen to simply display the deconvolved source time functions, two stations for each event, at a range of depths. The results which are shown in Figure A3 include source time functions for a suite of depths, from which the best depth extent can be determined based on the simplicity and consistency of the source time function. Depth assumptions which overestimate the true depth of an event produce periodic moment pulses in the deconvolved source time functions. Our best depth estimates are shown by the heavy bars in Figure A3 and are listed in Table A1 and Table 4. While the source time functions determined for these shallow events are not particularly simple at any particular value of depth, it is obvious from the results shown that these events are indeed very shallow.

TABLE A1. List of Large Outer Rise Earthquakes Studied in the Appendix

		Magnitude		Independent Depth		Tectonic	Focal Parameters					
No.	Date	M_b	M_s	Estimate, km	References	Class T/C	AZI,	Dip,	Slip/AZI,	Dip,	Slip	References
K2	March 16, 1963	7.7	----	10.-50.	T	C	16,	55,	90/196,	35,	90	SB66
J2	Nov. 21, 1969	6.4	7.7	0.-20.	T	T	23,	86,	6/292,	84,	175	F72
S4	Aug. 17, 1972	6.3	7.1	0.-6.	T	T	95,	58,	-115/316,	40,	-56	T
T7	July 2, 1974	6.5	7.2	5.-30.	T	C	65,	23,	137/197,	75,	73	C&F
T9	Oct. 11, 1975	6.4	7.8	0.-35.	T	C	0,	29,	68/205,	63,	102	T
P3	Oct. 31, 1975	6.4	7.2	----	----	T	30,	50,	-143/274,	63,	-46	T
T10	April 2, 1977	6.4	7.6	5.-25.	T	C	170,	60,	85/ 0,	30,	99	T
S8	July 29, 1977	6.3	7.2	0.-15.	T	SS	200,	88,	150/291,	60,	2	T
T14	June 17, 1978	6.5	7.0	0.-20.	T	T	190,	60,	-90/ 10,	30,	-90	T

References are the same as in Table 3.

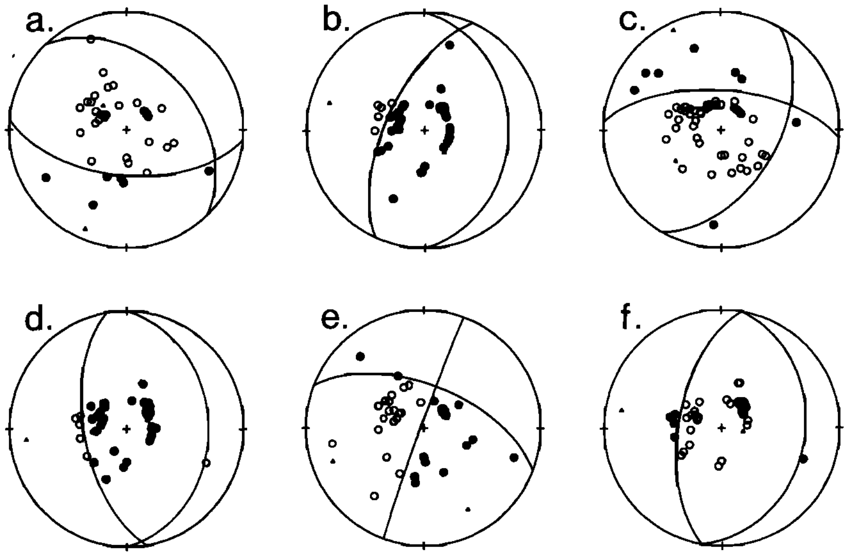

Fig. A1. Lower hemisphere equal-area focal mechanisms of large outer rise events. Solid circles are compressional first motions, and open circles are tensional first motions. The focal mechanisms are for events on (a) August 17, 1972, (b) October 11, 1975, (c) October 31, 1975, (d) April 2, 1977, (e) July 29, 1977, and (f) June 17, 1978.

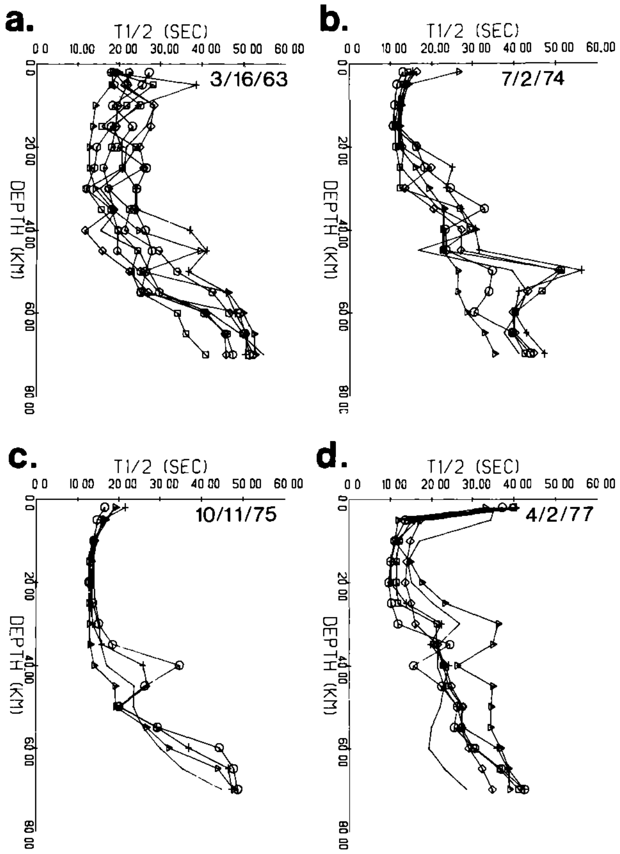

Fig. A2. T1/2 versus depth curves for compressional outer rise events on (a) March 16, 1963, (b) July 2, 1974, (c) October 11,1975, and (d) April 2, 1977. Depth profiles for several stations are shown for each event. The best depth distribution for each event is shown by the heavy bar and corresponds to low values in the parameter T1/2 [see Christensen and Ruff, 1985].

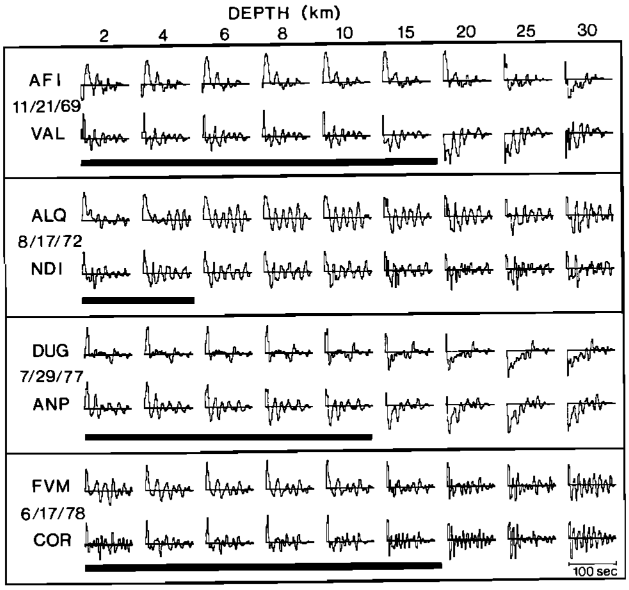

Fig. A3. Deconvolved source time functions for tensional outer rise events. Two stations are deconvolved for each event. The source time functions for each station are deconvolved using a point source assumption at the depths shown. The best depth distributions shown by the heavy bars correspond to the simplest and most consistent source time functions. Depth assumptions which overestimate the true depth of an event produce periodic moment pulses in the deconvolved source time functions [see Christensen and Ruff, 1985].

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