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SEISMIC HISTORY AND SEISMOTECTONICS OF THE SUNDA ARC

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Abstract. Historic records of the last 300 years reveal two great interplate earthquakes (1833, $M_w = 8^3/_4$; 1861, $M_w = 8^1/_4$-$8^1/_2$), which ruptured major segments of the Sumatra fore arc in western Indonesia; a significant percentage of interplate slip along this portion of the plate boundary appears to occur seismically. The ends of these rupture zones are coincident with clusters of large ($M_s \geq 7$) and moderate ($6 \leq M_s \leq 7$) shocks and with heterogeneities in the plate interface as inferred from geologic and geophysical data. The northern extent of the 1833 rupture zone is coincident with a group of moderate and large earthquakes, a structural arch in the fore arc, and a fracture zone on the subducted plate. The southern portion is coincident with a very prominent cluster and the along-strike extension of a sediment-filled trough on the subducted plate. Prior to this study, Sumatra was characterized as relatively aseismic as inferred from the lack of great earthquakes in the instrumental record of this century. Java and the Lesser Sunda Islands had major ($M_s \geq 6$) earthquakes in the historic record, but none are of the same magnitude as the great events near Sumatra. There is no clear evidence that shocks in the Java fore arc were interplate events, yet geophysical data indicate recent uplift of the trench slope break and a change in strike of the trench axis where the northernmost flank of the Roo Rise, a prominent bathymetric high, appears to be interacting with the fore arc. This feature was formed at a ridge crest and is more buoyant, and thus more difficult to subduct, than the surrounding seafloor. There is no increase in seismicity associated with this tectonism, however, that may indicate a lack of contact between the crystalline portions of the plates at this time. We infer that a majority of slip on the plate interface near Java occurs aseismically. The variation in occurrence of great interplate earthquakes along the Sunda Arc may be interpreted in terms of a model that attributes variation in interplate coupling to the age of the subducted lithosphere. Great interplate earthquakes occur near Sumatra, where the age of the youngest crust is 46 Ma. The characteristics of the Sunda Arc, and analogies with Pacific arcs, imply that the entire length of Sumatra has the potential to produce great thrust earthquakes; its seismic potential should be considered high (as there has been no recurrence of the great events of 1833 and 1861). In contrast, no such events have been reported off Java and the Lesser Sunda Islands, where the oldest crust is 152 Ma. The plate interface near Java and the Lesser Sunda Islands should be considered to have low seismic potential.

Introduction

Long-term seismic slip rates and present-day seismic potential for any plate boundary may be estimated by characterizing the spatial extent and repeat time of great ($M_s \geq 7^3/_4$) earthquakes, since large and great earthquakes ($M_s \geq 7$) release a high percentage of the strain energy [Brune, 1968] accumulated during the earthquake cycle. Rupture zones of great earthquakes tend to abut without significant overlap and to fill in gaps that have been quiescent for such events during the past 30 to 100 years [Fedotov, 1965; Mogi, 1968]. Many present-day seismic gaps have a history of great earthquakes during the past several centuries and strain energy accumulating in these gaps will be released by the occurrence of future large earthquakes [Tobin and Sykes, 1968; Sykes, 1971; Kelleher, 1972; Kelleher et al., 1973]. These seismic gaps, which have not experienced large earthquakes for tens to hundreds of years, have the highest seismic potential. Some plate boundaries, however, have no historic record of large earthquakes. Along these segments, relative plate motion may occur by aseismic slip, small and moderate magnitude earthquakes, or the historic record may be shorter than the recurrence interval for large shocks in that region.

The occurrence of large and great earthquakes is affected by plate tectonic parameters which vary significantly from arc to arc (e.g. convergence rate and direction, age of the subducted plate, dip of the Benioff zone, nature of the crust of the upper plate); and the extent of their rupture zones is affected by heterogeneities in the plate interface. Tectonic segmentation of an arc may occur by the subduction of bathymetric highs on the subducted seafloor [Ando, 1975; Kelleher; 1972, McCann and Sykes, 1984; Isacks and Barazangi, 1977] or by the block-like nature of the overriding plate [Carr et al., 1974; Mogi, 1969]. Such features act as lateral heterogeneities in the prevailing physical properties (stress, strength) of the arc, and these differences may be reflected in the seismicity. Along-strike changes in the level of seismic activity [McCann et al., 1982; Vogt et al., 1976] as well as effects on the boundaries of rupture zones of large earthquakes have been correlated with these types of tectonic features [Kelleher and McCann, 1977; Nishenko and McCann, 1979; Abe, 1973].

In this study, earthquake intensity maps are derived from the historic record (1681-1921) and a homogeneous catalog of instrumentally recorded events (1903-February, 1985) is developed. The spatial extent of rupture zones of great thrust earthquakes, as delineated by felt reports and tsunami data, and locations of other large shocks are determined. The tectonic framework of this margin is studied with geophysical data available for the Sunda Arc and northeast Indian Ocean. We have examined the relationship between earthquakes and geophysical features, which may act as spatial heterogeneities on the plate interface (and possibly influence the subduction process), and the gross characteristics of the overriding and subducted plates (and possible effects on mode of strain energy release). Various segments of the Sunda Arc margin are characterized in terms of typical size of gap-filling earthquakes, average repeat times for large shocks, mode of subduction (i.e., seismic versus aseismic), and seismic potential.

Tectonic Setting and Plate Kinematics

The Sunda Arc extends over 5600 km between the Andaman Islands to the northwest and the Banda Arc to the east, resulting from convergence between the Indo-Australian plate and Southeast Asia (Figures 1 and 2). Many characteristics of the Sunda Arc change significantly along strike. Fore arc geometry systematically varies from west to east (the depth of the fore arc basins, trench slope break, and trench increase toward Java) as the sediment thickness on the subducted plate decreases. A relatively simple style of subduction occurs where oceanic crust is subducted beneath the continental platform of Sumatra and western Java as well as the island arc of eastern Java and the western Lesser Sunda Islands. More complex tectonic systems exist in the Andaman Islands, where convergence is essentially subparallel to the arc [Curray et al., 1978], and east of Java, where collision of the island arc of the Lesser Sunda Islands and the Australian continent occurs [Silver et al., 1983].

Interplate motion, normal to the arc near Java, becomes oblique at Sumatra, where motion parallel to the arc is accommodated by dextral strike-slip displacement along the Sumatra Fault System (Figure 2), probably the world's clearest example of this type of major shear fault system adjacent to a convergent margin [Fitch, 1970a; 1972]. This fault system, consisting of about 20 separate en echelon segments [Tjia, 1978], extends for 1600 km along the volcanic chain of western Sumatra. It may be traced into the fore arc south of Sumatra and appears to turn into a complex pattern of extensional faults [Huchon and Le Pichon, 1984]. North of Sumatra, the fault system extends into the Andaman

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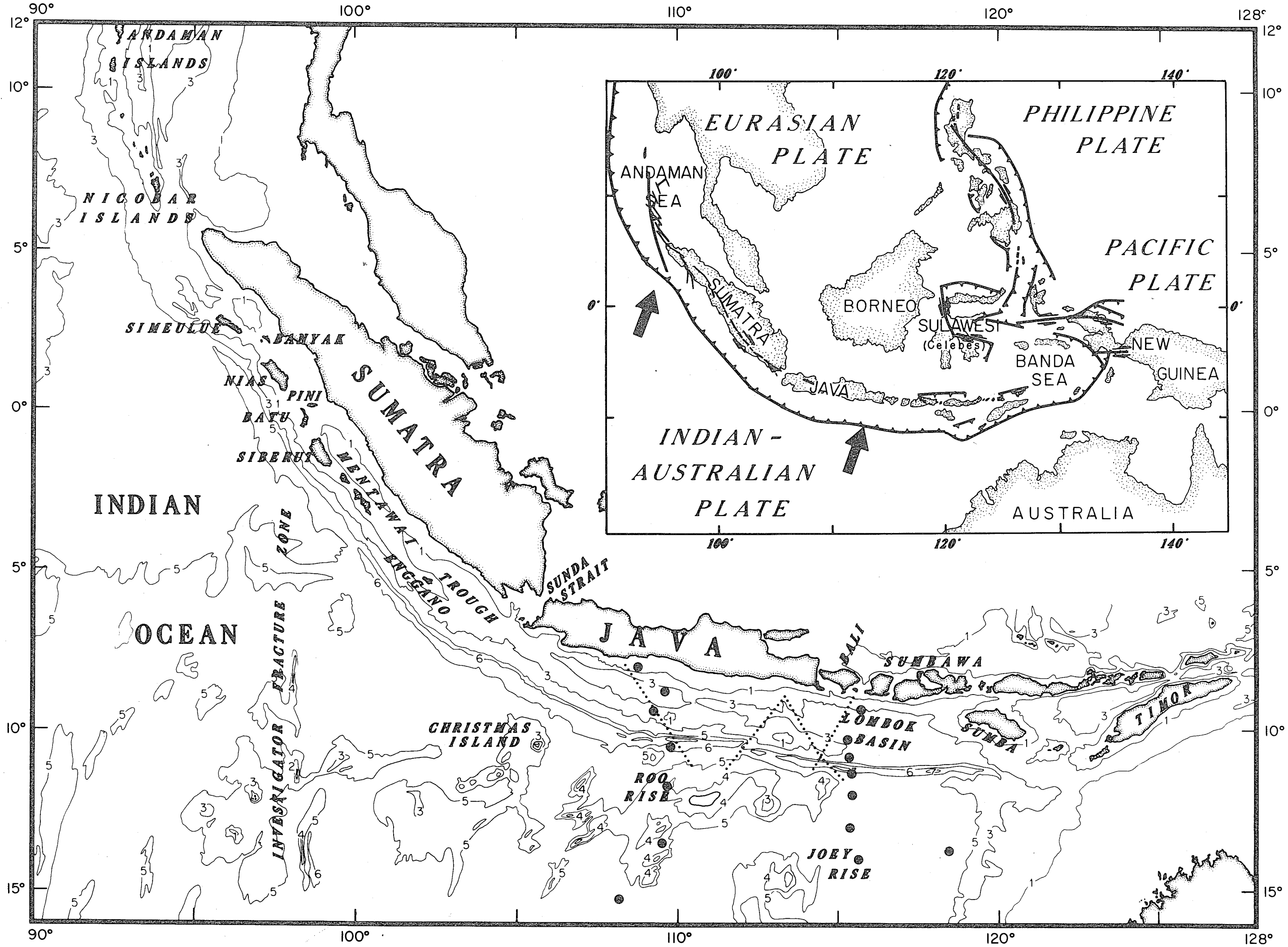

Fig. 1. Plate tectonic setting and kinematic motion (as determined by Minster and Jordan, [1978]) for Southeast Asia. Bathymetry is from Hamilton [1979], major faults and plate boundaries are from Curray et al. [1978], Tjia [1978], Karig et al. [1980], McCaffrey et al. [1980, 1985], and Hayes and Taylor [1978]. The location of reflection profiles in figure 8 (dotted lines) and the location of the refraction profiles (dots) in figure 9 are shown.

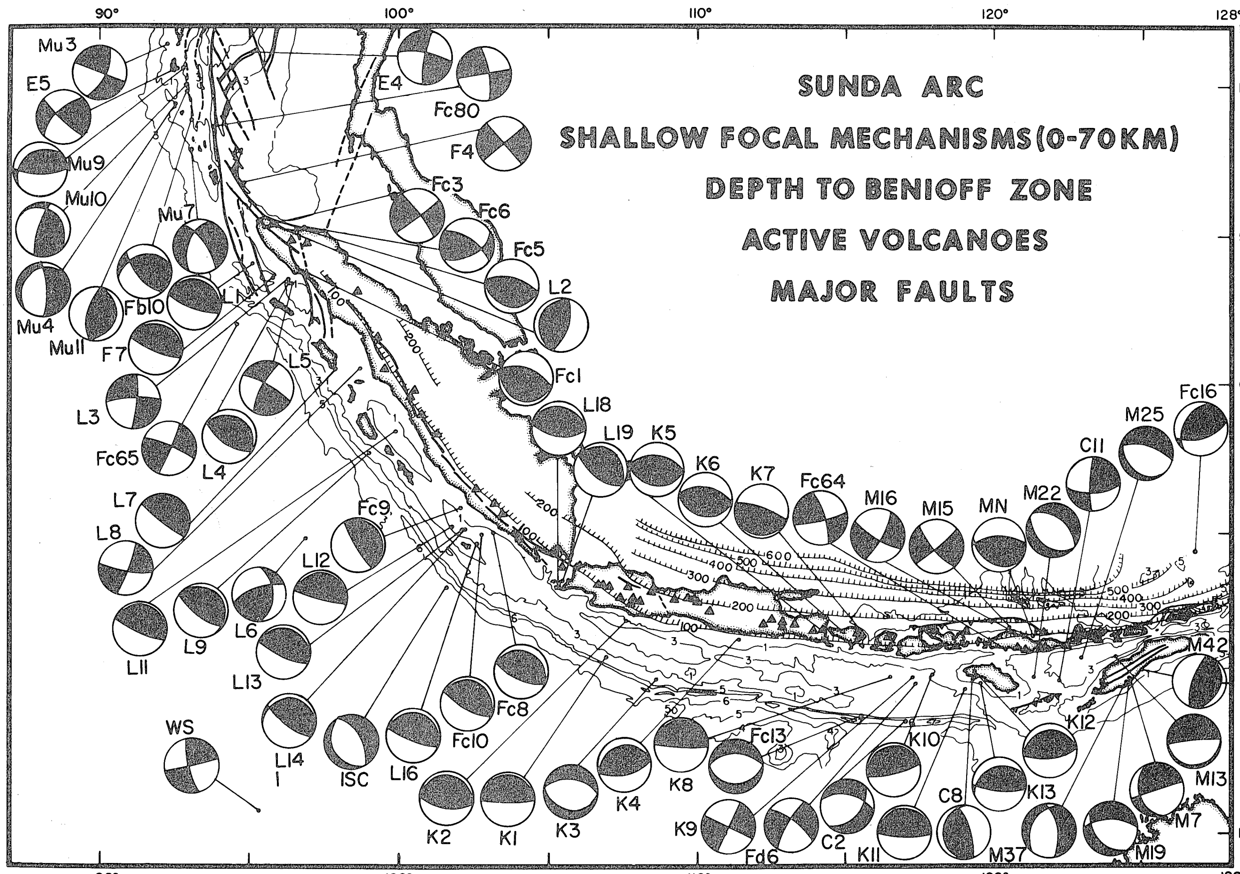

Fig. 2. All published focal mechanisms for shallow (z ≤ 70 km) earthquakes of the Andaman Islands, Sumatra, Java, and the Lesser Sunda Islands (references given in Table 1); depth to Benioff zone (hatachured lines represent 100 km depth contour interval determined from figure 6); active volcanoes denoted by triangles [Simkin et al., 1981]; major faults are denoted by dark solid lines (references given in Figure 1).

Basin, where it most likely joins the fracture zones of the back arc spreading center near the Andaman Islands [Curray et al., 1978]. Geologic evidence of displacements (stream and lithologic offsets, geodetic measurements after the 1892 Tapanoeli earthquake [Katili, 1974], fault plane solutions in the Andaman Basin) confirm that the motion is right-lateral. Rate of fault motion, estimated from geologic parameters, varies by an order of magnitude [Rock et al., 1982]. Major right-lateral faults crossing the fore arc have been mapped near the Banyak Islands [Karig et al., 1980]. No similar shear faulting of regional extent exists in Java.

The kinematics of Southeast Asia and its plate boundaries are not precisely defined. Minster and Jordan's [1978] RM2 plate model predicts convergence at the Sunda Arc along an azimuth of about N20E. Their convergence rate varies from 7.8 cm yr^{-1} near Sumba to 6 cm yr^{-1} near the Andaman Islands. Since no data from the Sunda Arc itself were used to constrain the model, the relative pole of rotation between the Indo-Australian plate and the Eurasian-China plate is one of the most poorly determined. The pole's location is also likely to be affected by the Sumatra Fault System and internal deformation within the Indo-Australian plate, where a partial localization of deformation occurs in the vicinity of the Ninetyeast Ridge [Stein and Okal, 1978; Geller et al., 1983]. Convergence directions may be determined from slip vectors of focal mechanisms of interplate earthquakes in this region (Figure 2 and Table 1). Convergence by Sumatra is N26.8E; southern Sumatra is N25E (focal mechanisms Fc8, Fc10, L12, L13, L14, L16), central Sumatra is N26.3E (L7, L9, L11), and northern Sumatra is N31E (L1, F7, L4). Convergence by Java is N0.2W (K1, K2, K8, K12). As discussed by Jarrard [1986], it is unlikely that the azimuth of convergence is significantly biased near Java, as there are no pervasive strike-slip faults accommodating a significant portion of the slip between the two plates. The true direction of convergence between Southeast Asia and the Indo-Australian plates along the Sunda Arc is probably close to N-S. Vector diagrams that incorporate motion between Indo-Australia and the Sumatra fore arc (N26.8E) and motion between Indo-Australia and Southeast Asia (N0.2W) predict a maximum right-lateral motion along the Sumatra Fault System of 3.6 cm yr^{-1}.

The age and thickness of the subducted oceanic crust increases from Sumatra to Java. The increasing dip and depth of penetration of the Benioff zone reflect this change (Figure 3). West of the Sunda Strait, seismic activity does not extend below 200 km. Slab configuration is ambiguous in northern Sumatra while in the south a plane dipping 40°-50° is apparent. By Java, seismic activity extends from the surface to a depth of 650 km with a gap in seismicity between 300 and 500 km. By Timor, the continuity of the slab to its greatest depth has been documented [Cardwell and Isacks, 1978]. It is within this tectonic setting that we examine the occurrence of earthquakes in the historic record and large and moderate earthquakes of this century.

Historical Intensity Data

The seismic history of the Sunda Arc from the late 1600's through the time of early instrumental recording (about 1900) is investigated as reported in the Indonesian Journal of Natural Sciences [Anon, 1863-1922] and by Wichmann [1918, 1922]. The quality of this historic earthquake intensity data depends upon the density of population and settlement by Europeans; it is difficult to assess the full extent of the effects of an earthquake everywhere. Reports of the earliest events were sometimes so brief that the maximum intensity in a region was not possible to determine; only the damage that was reported could be used.

Approximately 60 intensity maps were made in this study, enabling

TABLE 1. Shallow Focal Mechanisms (0-70 km) of the Sunda Arc

Key From Figure 2	Date	Latitude	Longitude	Depth, km	Depth Reference
C2	May 28, 1972	-11.05	116.97	45	C
C8	April 10, 1973	-9.81	119.29	55	C
C11	Nov. 5, 1972	-9.82	122.17	45	C
E4	March 29, 1971	11.16	95.11	17	E
E5	July 9, 1973	10.66	92.59	44	E
F4	Nov. 30, 1964	6.8	94.8	32	F
F7	Aug. 21,1967	3.6	95.8	33	F
Fb10	Sept. 15, 1964	8.9	93.1	32	Fb
Fc1	April 3, 1964	4.0	96.6	70	Fc
Fc3	April 2, 1964	5.8	95.5	16	Fc
Fc5	April 12, 1967	5.3	96.5	55	Fc
Fc6	June 15, 1964	5.3	96.8	67	Fc
Fc8	April 7, 1963	-4.9	103.2	46	Fc
Fc9	July 17, 1963	-4.10	102.2	69	Fc
Fc10	Oct. 24, 1963	-4.9	102.9	65	K
Fc13	March 30, 1967	-11.0	115.5	32	Fc
Fc16	April 22, 1967	-5.6	126.8	32	Fc
Fc64	Jan. 26, 1968	-8.8	120.4	29	Fc
Fc65	Nov. 21, 1969	-2.0	94.6	20	Fc
Fc80	July 2, 1967	8.7	93.8	30	Fc
Fd6	Oct. 7, 1977	-9.99	117.28	12	Fd
ISC	Nov. 11, 1982	-6.65	101.63	33	ISC
K1	July 27, 1976	-9.01	106.91	46	K
K2	Aug. 14, 1977	-7.89	107.55	55	K
K3	Sept. 7, 1974	-9.80	108.49	60	K
K4	July 3, 1971	-8.51	111.36	59	K
K5	July 14, 1976	-8.17	114.17	56	K
K6	July 14, 1976	-8.21	114.87	53	K
K7	May 18, 1963	-8.25	115.53	52	K
K8	Feb. 9, 1966	-9.75	116.46	35	K
K9	July 31, 1975	-9.77	117.24	52	K
K10	May 20, 1975	-9.61	118.92	15	K
K11	Jan. 2, 1977	-10.16	119.03	19	K
K12	Dec. 19, 1973	-9.52	119.39	42	K
K13	Sept. 18, 1972	-9.93	119.60	23	K
L1	Nov. 13, 1976	4.14	95.14	37	K
L2	Dec. 17, 1975	5.28	95.90	44	K
L3	Oct. 30, 1976	3.54	96.28	25	K
L4	June 20, 1976	3.4	96.32	42	K
L5	June 21, 1976	3.4	96.40	17	K
L6	June 26, 1971	-5.18	96.90	21	L
L7	Dec. 4, 1974	0.5	97.89	20	L
L8	Feb. 4, 1971	0.53	98.72	40	L
L9	Dec. 24, 1974	-2.30	99.01	32	L
L11	Dec. 19, 1970	-1.59	99.95	46	L
L12	July 20, 1976	-4.73	101.82	35	K
L13	Jan. 10, 1975	-4.83	102.24	47	L
L14	Sept. 30, 1975	-4.85	102.26	63	K
L16	Oct. 4, 1976	-5.27	102.65	63	L
L18	May 4, 1971	-6.54	105.37	46	L
L19	Nov. 9, 1975	-6.44	105.38	55	L
M7	July 18, 1982	-9.69	124.07	49	M
M13	Aug. 2, 1982	-9.06	124.03	46	M
M15	Aug. 6, 1982	-8.10	120.52	25	M
M16	Aug. 6, 1982	-8.18	120.64	26	M
M19	Aug. 7, 1982	-10.00	124.49	42	M
M22	Aug. 9, 1982	-9.74	121.34	02	M
M25	Aug. 10, 1982	-9.02	122.97	54	M
M37	Aug. 28, 1982	-9.91	124.43	50	M
M42	Sept. 10, 1982	-9.49	125.05	04	M
MN	Dec. 23, 1978	-8.33	121.34	11	MN
Mu3	Feb. 16, 1974	11.47	92.32	19	Mu
Mu4	June 5, 1971	09.4	92.5	25	Mu
Mu7	July 11, 1961	07.88	93.07	51	Mu
Mu9	Sept. 16, 1964	10.71	92.81	40	Mu
Mu10	Nov. 5, 1971	10.1	92.9	53	Mu
Mu11	May 6, 1970	09.81	92.91	32	Mu
WS	Oct. 31, 1965	14.23	95.27	24	WS

Key for focal mechanisms in this table and figure 2: C, Cardwell and Isacks [1978]; E, Eguchi et al. [1979]; F, Fitch [1970a]; Fb, Fitch [1970b]; Fc, Fitch [1972]; Fd, Fitch et al. [1981]; ISC, International Seismology Center [1978]; K, Kappel [1980]; L, Lawrence, unpublished data (1978) as reported by Kappel [1980]; M, McCaffrey et al. [1985]; MN, McCaffrey and Nabelek [1984]; Mu, Mukhopadhyay [1984]; WS, Wiens and Stein [1983].

us to characterize events that clearly have an inland epicenter and events of submarine origin that are clearly not associated with intraplate faults (Figures 4a, 4b, 4c). Included in this paper are all possible subduction zone earthquakes as determined by reports of either intensity patterns centered on the fore arc basin, tsunamis, or seaquakes (i.e., events felt at sea). The great events of 1833 and 1861 are clearly unequaled, and the vast majority of large shocks are reported from Sumatra, even though it was less densely settled than neighboring Java, implying that long-term levels of seismic activity are higher in Sumatra than Java. Place names in text are noted in Figure 1.

Earthquakes in Sumatra

December 11, 1681. The first report available is very general, but indicated that a "strong earthquake" shook the mountains in this particular province and a seaquake was observed.

November 3, 1756. In 1756, the first good intensity report is available. Here, walls in buildings constructed by the Dutch colonial government collapsed, as well as many houses and entire towns in the region. While exhibiting severe damage, no tsunami was reported. The intensity pattern is dissimilar to events associated with the Sumatra Fault System and several characteristics of this shock are very similar to those of the 1914 event, which was clearly of submarine origin.

No date, 1770. The 1770 shock caused severe damage in the same general area as the 1756 event, but a tsunami was associated with it. An eruption of the nearest volcano occurred simultaneously with this event.

February 10-11, 1797. In 1797 a large earthquake caused moderate damage, and a tsunami was observed in ports on the coast of the mainland and on the Batu Islands. Numerous aftershocks occurred in the next week.

March 18, 1818. A very strong shock was reported and associated with both a tsunami and a seaquake. People on land were thrown out of bed, suggesting Modified Mercalli (MM) Intensity IX; the reports of two ships at sea state, "sailors had been thrown out of their hammocks." Seaquakes at a distance of "over 200 miles from the coast" were reported. Aftershocks were felt for at least 3 weeks afterwards. Two months later (May, 1818) a significant aftershock and associated seaquake were reported.

November, 24, 1833. The great earthquake of 1833 had maximum intensities and generated a tsunami over 550 km along the south central coast of Sumatra. It was felt in Singapore and Java and even caused "rents" in houses on the east coast of Sumatra (about 300 km from the west coast). Many buildings on the west coast, in both the northernmost and southernmost regions of highest intensity, completely collapsed. "Two-foot-wide cracks in the ground" were observed. A powerful tsunami also caused much damage on the coast. Aftershocks were reported for many days. One particular aftershock on November 25 was felt near the Banyak Islands.

This event appears to have ruptured the entire plate margin from the southern island of Enggano to the latitude of the Batu Islands. The moment of the great 1833 earthquake may be estimated by using a rigidity of $\mu = 5 \times 10^{11}$ dyn cm^{-1} (an average value of the shear modulus for the depth range involved in great thrust earthquakes), an average slip of u = 4.25-7.5 m (range of values determined by empirical relationships established by Sykes and Quittmeyer [1981]), a fault width of w = 100 km (a minimum estimate of interface width), and a fault length of l = 550 km (the extent of the highest intensities). The moment $M_o = \mu uwl$ = 1.2-2.1x10^{29} dyn cm is equivalent to the moment magnitude M_w = 8.7-8.8, which places this event in the category of one of the 10 largest events of the past two centuries [Kanamori, 1977].

January 5-6, 1843. The 1843 event caused severe damage on the island of Nias, where many houses were destroyed; buildings sank, suggesting liquefaction of sediments. A tremendous tsunami wiped out towns on the east coast of Nias and reached the main coast. The damage and associated tsunami were very localized.

November 11, 1852. In 1852 another earthquake, associated with a seaquake, was felt in the same area.

February 16, 1861. A great event occurred in February 1861. This earthquake was felt from the Malay Peninsula to central and eastern Java and appears to have ruptured a major segment of the plate boundary in northern Sumatra. The highest intensities extend for 300 km along the coast, and the tsunamis generated extended over 500 km along the arc.

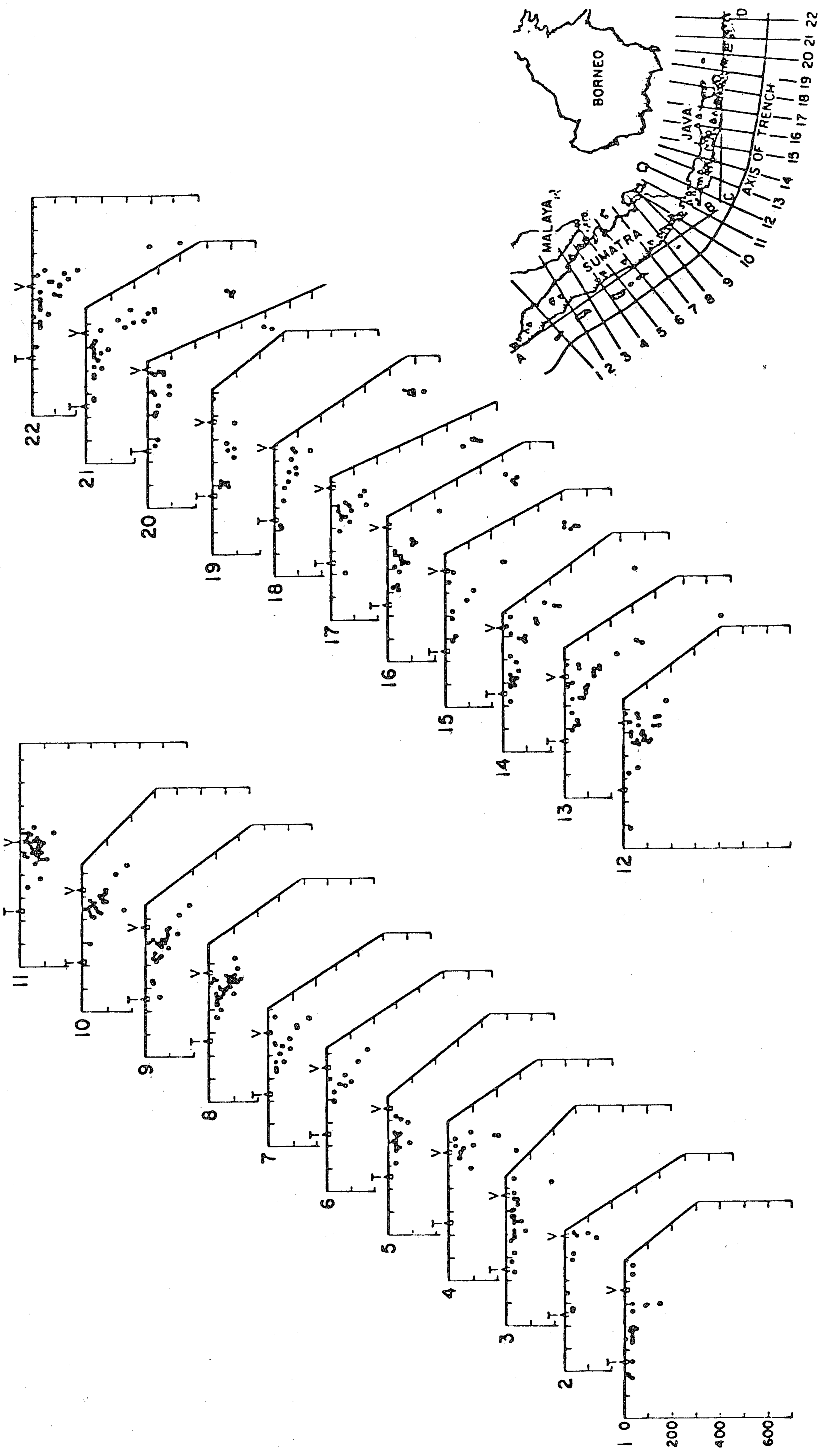

Fig. 3. Vertical cross sections of seismicity projected perpendicular to the strike of the trench. Events from 1962-1975 with 15 or more stations reporting were plotted. Positions of the trench and volcanic axis are shown. By Sumatra, the greatest depth of events is approximately 200 km. Java has events occurring deeper than 600 km.

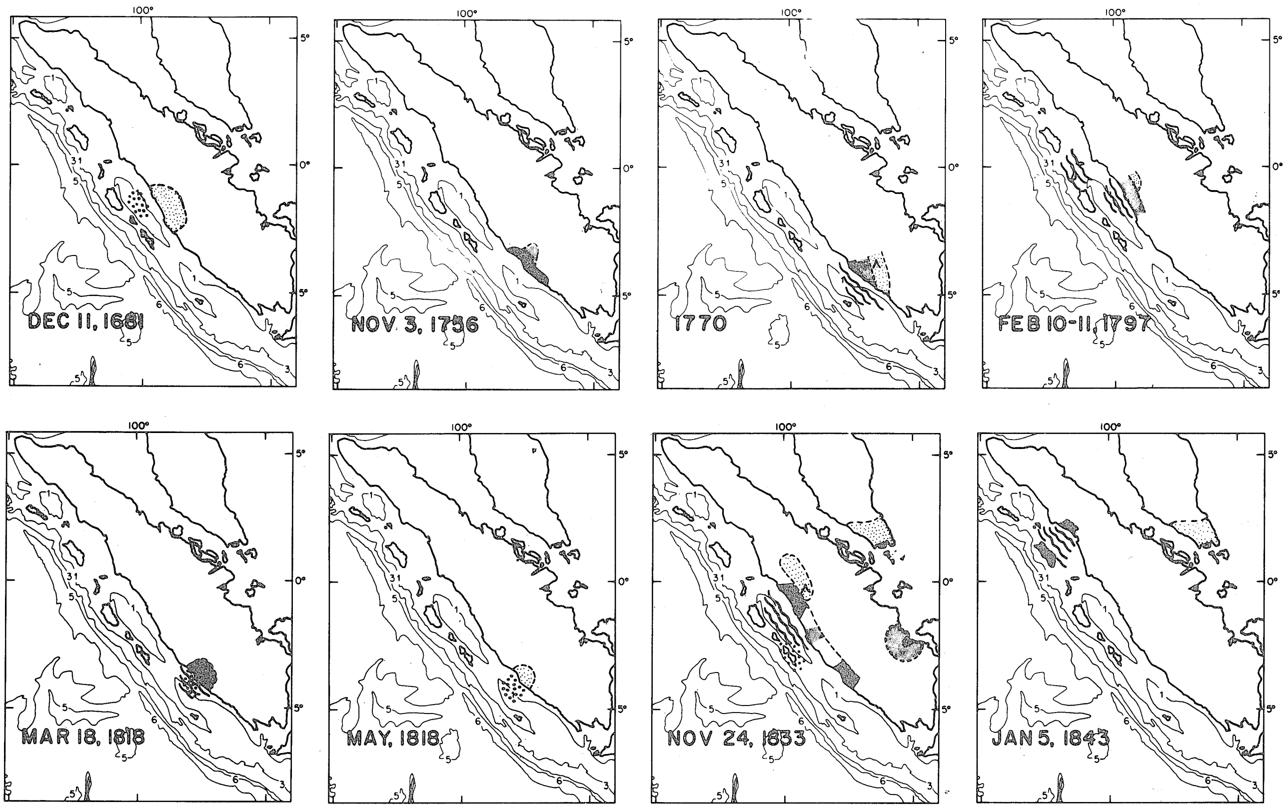

Fig. 4a.

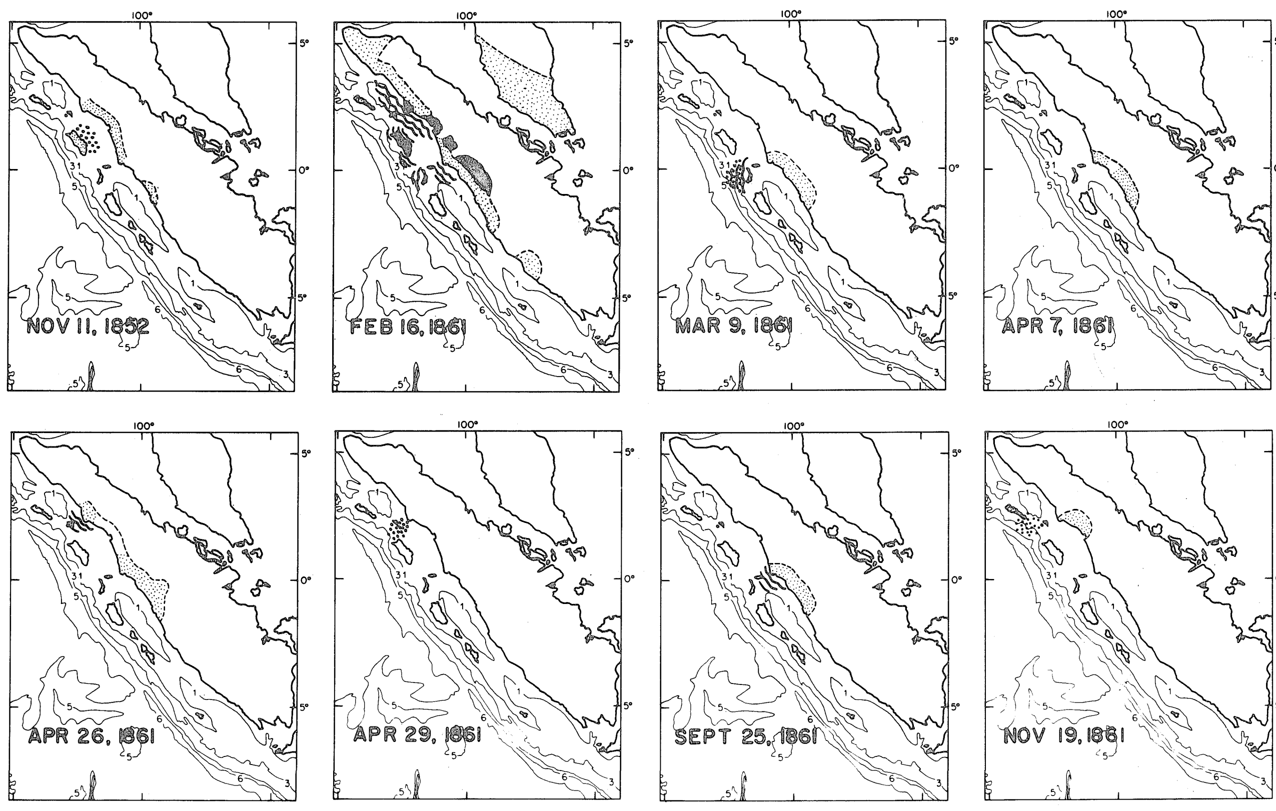

Fig. 4b.

Fig. 4. Intensity maps of the possible subduction-related earthquakes of the Sunda Arc in order of presentation in text. Light density dots indicate Modified Mercalli Intensity (MM) = I-IV, moderate density dots indicate MM = V-VII, black indicates MM ≥ VIII. Inverted "V" signifies volcanic eruption simultaneous with earthquake. Heavy wavy lines indicate the extent of the tsunami. Heavy dots indicate report of a seaquake. Epicenters for shocks of this century are shown as determined by Richter [1958] and Gutenberg and Richter [1954]. Only the September 11, 1921, earthquake had a relocatable epicenter, which is plotted.

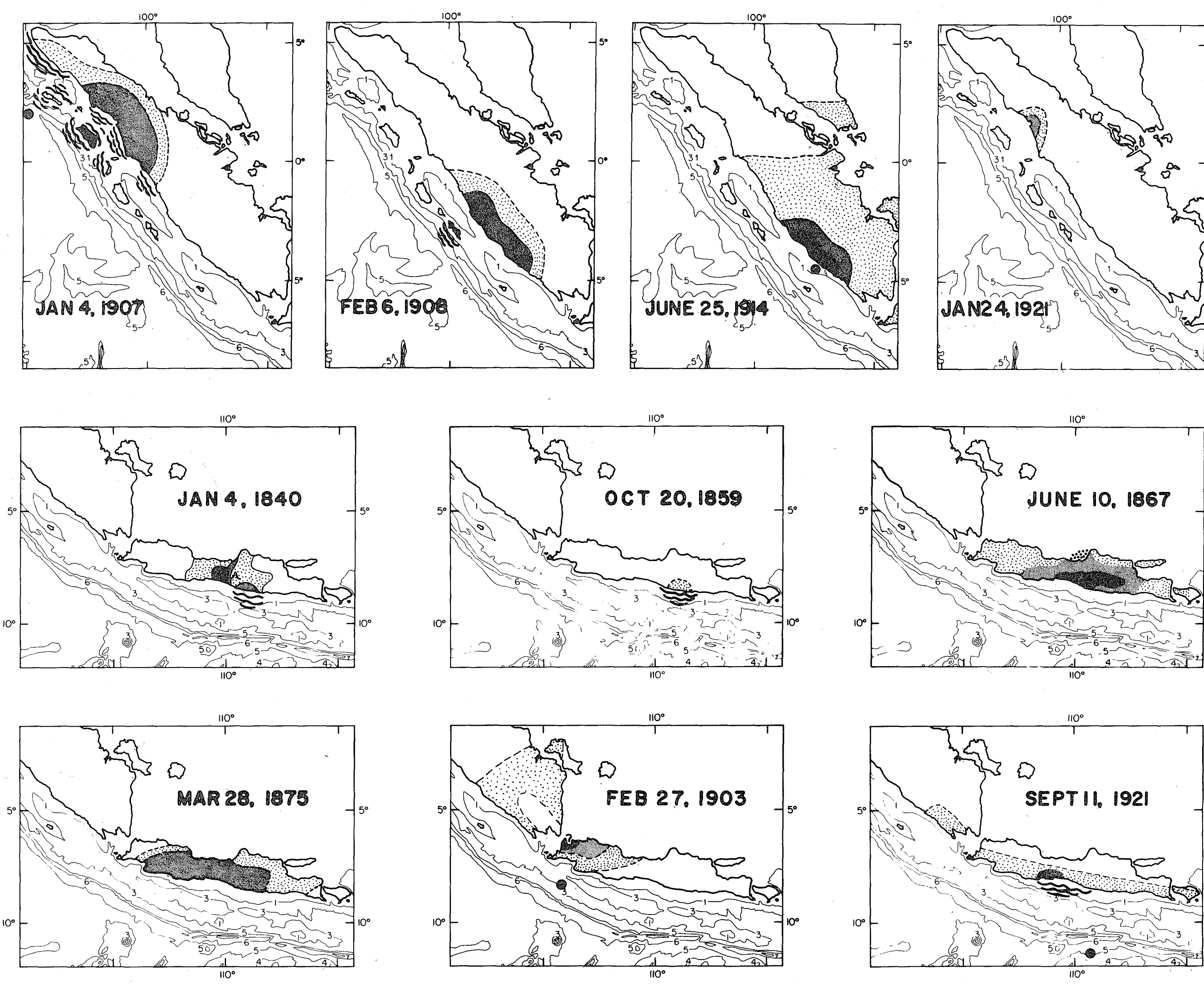

Fig. 4c.

Houses collapsed on the mainland. On Nias, people were thrown off of their feet. This earthquake appears to have taken place between the trench and the islands of the trench slope break, since the tsunami devastated towns on the seaward side of the Batu Islands, and a town on the southwest shore of Nias experienced a tsunami height of 7 m. Evidence for coseismic uplift exists on the north and west coasts of Nias, where piers of rock and reefs became exposed; a small island became connected to Nias. On Java, more than 1400 km away, seiches were reported in six different bodies of water, and the quake was felt as far as 1600 km from Nias.

This rupture zone lies between two bathymetric and structural highs (Banyak Islands and Batu Islands), and is the adjoining segment to the 1833 rupture zone. The moment of the great 1861 event was estimated by using $\mu = 5\text{x}10^{11}$ dyn cm^{-1}, w = 100 km, 1 = 300 km, and u = 2.75-5 m. The moment of the 1861 earthquake, $M_o = 4.1\text{-}7.5\text{x}10^{28}$ dyn cm, is equivalent to the moment magnitude $M_w = 8.3\text{-}8.5$.

In the next 7 months, six aftershocks occurred; five events had intensity patterns centered on the trench slope break or the fore arc basin.

March 9, 1861. This event was felt on the mainland and on the Batu Islands where it was accompanied by a seaquake and tsunamis; April 7, felt on the mainland; April 26, felt on the mainland, with an associated tsunami in the north; April 29, seaquake and shock felt on the Banyak Islands; September, 25, shock occurred with a damaging tsunami; November seaquake occurred near island of Siberut. The shock was felt on the mainland.

Almost 50 years elapsed until another major shock occurred.

January 4, 1907. This event caused tsunamis that devastated Simeulue and extended over 950 km along the coast (the extent of this tsunami appears to be greater than the 1861 event only because tide gauges were in use at this time). People on Nias were not able to stand. The shock was probably located seaward of the trench slope break, since islands on the seaward side of Nias and towns on the seaward side of the Batu Island were devastated by the sea wave. Gutenberg and Richter [1954] have assigned this event a magnitude M = 7.6. The location they report, seaward of the trench by Simeulue, is inconsistent with that expected from the extent of moderate intensities in the interior of Sumatra. We prefer an epicenter seaward of the trench slope break but landward of the trench. Aftershocks were reported for 8 days. While this was an intense shock, the damage was localized.

February 6, 1908. The 1908 event is not noted by Gutenberg and Richter [1954], which implies that it was not large enough to be included in the early portion of their catalog; its magnitude is likely to be less than 7. Only moderate intensities were observed. This shock probably occurred seaward of the trench slope break since tsunami damage was reported on the seaward side of the islands.

June 25, 1914. This event was assigned M = 7.6 by Gutenberg and Richter [1954]. The consistency between the reported epicenter and the intensity pattern suggests that the location for this shock is fairly well determined, indicating that this may be an interplate event, as are other large shocks at these coordinates. In the region of highest intensity, many European houses and government buildings were destroyed, and nearly all were damaged. Landslides and sinking of coastal roads, up to 75 cm, were reported, possibly indicating liquefaction of clays in coastal sediments. While the intensity pattern and epicentral location indicate a submarine origin, no tsunami was reported with this event.

January 24, 1921. In 1921 another shock not noted by Gutenberg and Richter [1954] had intensity patterns centered around the fore arc basin, contrasting with intensity patterns of earthquakes along the Sumatra

Table 2. Major Earthquakes of the Sunda Arc

Large and Great Shallow Earthquakes of the Sunda Arc (1903 - Feb.1985)

Date	Latitude	Longitude	Depth	Reloc	GR	Abe	M_sWWSSN
Feb. 27, 1903	-8.00	106.00	25		8.1(R)	7.9(KA)	7.6
Jan. 4, 1907	2.00	94.50	50		7.6	7.6	7.3
June 3, 1909	-2.00	101.00			7.6	7.7	7.7
June 25, 1914	-4.50	102.50			7.6	7.6	7.6
Sept. 11, 1921	-11.35	110.76		R	7.5	7.5	7.5
March 26, 1930	-7.80	125.62	40	R	7.2	6.9	6.9
Feb. 10, 1931	-5.45	102.88		R	7.1	7.2	7.2
Sept. 25, 1931	-5.10	102.61		R	7.4	7.5	7.5
June 24, 1933	-5.09	104.70		R	7.5	7.5	7.5
Aug. 3, 1935	4.39	96.34		R	7.0	7.0	7.0
Dec. 28, 1935	-0.06	98.21		R	7.9 7.7(GK)	7.7	7.7
Aug. 23, 1936	5.24	94.77	40	R	7.3	7.1	7.1
Sept. 19, 1936	3.50	97.50		R	7.2	7.2	7.2
Sept. 27, 1937	-8.88	110.65		R	7.2	7.0	7.0
June 26, 1941	12.16	92.57	60	R	8.1 7.7(GK)	7.7	7.7
April 1, 1943	-6.55	105.60	35	R	7.0	7.1	7.1
June 8, 1943	-2.82	102.09	50	R	7.4	7.3	7.3
June 9, 1943	-0.94	100.91	50	R	7.6	7.6	7.6
Jan. 5, 1944	-1.72	100.77	60	R	7.0	6.8	6.8
May 8, 1946	-0.51	99.31		R	7.1	7.1	7.1
June 24, 1949	-6.24	105.39	60	R	7.0	(-)	7.2
March 27, 1950	-5.81	102.87		R	7.0	(-)	7.2
Feb. 14, 1952	-7.73	126.53	66	R	$7\,^1/_4$	7.1	7.3
May 17, 1953	6.77	93.75			7.0 (B)	(-)	7.0
June 25, 1953	-8.60	123.81			7.0 (B)	6.8	7.0
May 17, 1955	6.77	93.75	10		7.0 (B)	(-)	7.0
May 15, 1962	-7.45	128.26	36		7.0 (B)	(-)	7.0
Feb. 4, 1971	0.50	98.68	40		7.1 M_sBSSA	(-)	7.1
Oct. 1, 1975	-4.90	102.20	33		7.0 M_sBSSA	(-)	7.0
June 20, 1976	3.40	96.33	33		7.0 M_sBSSA	(-)	7.0
Aug. 19, 1977	-11.16	118.41	33		7.9 M_sBSSA	8.1	7.9
Nov. 17, 1984	0.2	98.3	33		7.2 M_sBSSA	(-)	7.2

Moderate Shallow Earthquakes of the Sunda Arc (1953-Feb. 1985)

Date	Latitude	Longitude	Depth	Magnitude	Reference
June 25, 1953	-8.61	123.67	50	6.92	B
June 25, 1953	-8.60	123.81	33	7.00	B
June 26, 1953	-8.70	124.10		6.77	B
Oct. 14, 1954	-7.60	127.60		6.11	B
Nov. 2, 1954	-8.60	118.60		6.78	B
March 6, 1955	-1.80	100.40		6.03	B
March 22, 1955	-8.73	91.65		6.94	B
May 17, 1955	6.77	93.75		7.03	B
May 29, 1955	-10.30	110.50		6.38	B
Jan. 11, 1956	7.70	94.00		6.09	B
April 2, 1956	2.00	96.80		6.04	B
March 11, 1957	2.00	97.10		6.11	B
May 9, 1957	-9.00	107.20		6.21	B
May 12, 1957	-9.00	107.20		6.21	B
July 9, 1957	-6.20	104.10		6.02	B
April 6, 1959	-10.10	120.40		6.05	B
Nov. 26, 1959	-5.40	102.90		6.18	B
Nov. 26, 1959	-5.50	103.00		6.41	B
Oct. 26, 1961	-0.30	98.70		6.15	B
Dec. 21, 1962	-9.00	112.40		6.27	B
March 24, 1963	-9.70	120.40		6.08	F
Dec. 16, 1963	-6.40	105.40		6.13	F
June 15, 1964	5.40	97.00		6.10	F

TABLE 2. (continued)

Moderate Shallow Earthquakes of the Sunda Arc (1953-Feb. 1985)

Date	Latitude	Longitude	Depth	Magnitude	Reference
Sept. 15, 1964*	8.90	93.10	37	6.18	F
Nov. 30, 1964	6.80	94.80		6.31	F
Nov. 21, 1969	1.94	94.58	20	6.4	M_sBSSA
June 28, 1970	-8.75	124.04	50	6.2	M_sBSSA
Oct. 25, 1970	9.00	93.90	33	6.3	M_sBSSA
Dec. 19, 1970*	-1.60	99.90	46	6.2	M_sBSSA
Feb. 4, 1971*	.50	98.68	40	7.1	M_sBSSA
March 28, 1971	11.77	95.05	33	6.3	M_sBSSA
June 26, 1971*	-5.20	96.90	25	6.4	M_sBSSA
May 28, 1972*	-11.05	116.97		6.2	M_sBSSA
April 7, 1973	7.00	91.40	33	6.6	M_sBSSA
Feb. 16, 1974*	11.40	92.30	25	6.0	M_sBSSA
Feb. 16, 1974	11.40	92.40	33	6.1	M_sBSSA
Sept. 7, 1974*	-9.80	108.48		6.5	MsBSSA
Dec. 4, 1974*	.40	97.80	20	6.9	M_sBSSA
Dec. 24, 1974*	-2.30	99.00	33	6.8	M_sBSSA
July 30, 1975	-10.00	123.80	16	6.1	M_sBSSA
Sept. 30, 1975*	-4.90	102.20	33	6.0	M_sBSSA
Oct. 1, 1975	-4.90	102.20	33	7.0	M_sBSSA
Dec. 17, 1975*	5.30	95.90	17	6.2	M_sBSSA
June 20, 1976*	3.4	96.33	33	7.0	M_sBSSA
July 14, 1976*	-8.22	114.87	36	6.5	M_sBSSA
Jan. 2, 1977*	-10.17	118.99	19	6.0	M_sBSSA
March 8, 1977	.45	100.02	22	6.0	M_sBSSA
May 25, 1977	4.24	95.77	56	6.0	M_sBSSA
Aug. 19, 1977	-11.16	118.41	33	7.9	M_sBSSA
Aug. 20, 1977	-11.10	118.24	33	6.0	M_sBSSA
Aug. 20, 1977	-11.04	119.14	33	6.1	M_sBSSA
Aug. 25, 1977	-10.74	119.27	33	6.0	M_sBSSA
Aug. 27, 1977	-8.10	125.38	41	6.8	M_sBSSA
Sept. 21, 1977	-11.04	119.17		6.0	M_sBSSA
Oct. 7, 1977*	-9.95	117.32	33	6.3	M_sBSSA
Oct. 16, 1977	-9.73	117.12	33	6.0	M_sBSSA
April 10, 1978	-11.39	116.68		6.4	M_sBSSA
June 24, 1978	-5.16	102.35	33	6.4	M_sBSSA
Dec. 26, 1978	-8.43	121.45	54	6.5	M_sISC
Jan. 11, 1979	-4.08	101.25	32	6.2	M_sBSSA
July 24, 1979	-11.15	107.71	31	6.9	M_sBSSA
Sept. 29, 1979	1.18	94.32	30	6.8	M_sBSSA
Oct. 20, 1979	-8.32	116.02	33	6.2	M_sBSSA
Nov. 2, 1979	-7.66	108.25	25	6.0	M_sBSSA
Nov. 13, 1979	-4.45	102.04	44	6.3	M_sBSSA
Dec. 15, 1979	-3.39	102.61	33	6.6	M_sBSSA
Dec. 17, 1979	-8.41	115.96	33	6.3	M_sBSSA
May 15, 1980	-6.2	125.55	33	6.1	M_sBSSA
June 24, 1980	-5.98	103.96	43	6.0	M_sBSSA
Oct. 8, 1980	-5.37	103.12	33	6.3	M_sBSSA
Oct. 29, 1980	8.40	93.35	33	6.2	M_sBSSA
Jan. 20, 1982	-6.95	94.00	19	6.3	M_sBSSA
Jan. 20, 1982	7.12	93.94	27	6.2	M_sBSSA
March 11, 1982	-9.27	118.48	33	6.4	M_sBSSA
Aug. 7, 1982	-11.14	115.42	33	6.2	M_sBSSA
Jan. 22, 1983	-6.67	103.03	40	6.0	M_sBSSA
Jan. 22, 1983	-6.71	102.98	29	6.1	M_sBSSA
April 13, 1984	11.85	95.01	25	6.0	M_sBSSA
June 8, 1984	-5.80	104.17	33	6.1	M_sBSSA
Oct. 4, 1984	-9.81	118.79	34	6.3	M_sBSSA
Nov. 17, 1984	.20	98.30	33	7.2	M_sBSSA
Nov. 23, 1984	-7.99	102.26	33	6.7	M_sBSSA

Fault System at this latitude. It had no tsunami and did not appear to be very widespread, therefore not ruling out the possibility of an intraplate epicenter.

Earthquakes in Java

For Java, the historic record indicates only three major events which suggest a submarine origin.

January 4, 1840. The 1840 event had a very localized tsunami area and an unusual intensity pattern that partially reflects some of the structural trends on Java [e.g., Tjia, 1978], possibly implying an epicenter within the overriding plate.

October 20, 1859. This shock had low intensities and tsunami that affected only a limited region.

June 10, 1867. This event heavily damaged government and private buildings, with maximum intensities along the volcanic front. A seaquake was observed in the back arc. While no tsunami occurred and the high inland intensities follow structural trends, frequently indicating an inland epicenter, there are no pervasive strike-slip faults here. The regional extent of moderate and high intensities suggests that this event may have occurred on the plate interface.

March 28, 1875 The intensity pattern for this event is similar to the 1867 event except that no high intensities (MM ≥ VIII) were reported. The broad region of moderate intensity (MM = V-VII) could indicate that this is an intermediate depth event or it might imply an inland epicenter. No tsunami was noted for this event.

February 27, 1903. This event is the earliest instrumentally recorded shock reported by Richter [1958] for the Sunda Arc. It was assigned a magnitude M = 8.1 and located seaward of westernmost Java (Table 2). Kanamori and Abe [1979] have calculated a revised magnitude of M_s = 7.9. The intensity map, while incomplete, indicates the epicenter was located in northwestern Java or southeastern Sumatra. No tsunami was reported. The intensity pattern is similar to some inland events of Java that are not included in this paper. Consequently, the epicenter reported by Richter [1958] is likely to be inaccurate (approximately 200 km south of its true location); this event is not an interplate thrust event.

September 11, 1921. Gutenberg and Richter [1954] assigned this event a magnitude M = 7.5. The event was relocated in this study and its epicenter is on the Roo Rise, seaward of the trench in an intraplate setting (Table 2). This event was felt from southern Sumatra to Sumbawa, a distance of over 1600 km along the arc; tsunamis were reported for approximately 275 km along the coast. The intraplate setting of this event demonstrates that not all tsunamigenic earthquakes along Java are necessarily interplate thrust events.

Shallow Instrumentally Recorded Earthquakes and Tectonic Heterogeneities of the Plate Interface

A homogeneous catalog of epicenters of shallow, instrumentally recorded large earthquakes occurring during the interval 1900 to February 1985 and moderate earthquakes from 1953 to February 1985 was developed in this study (Table 2, method discussed in the Appendix). This catalog, plotted in Figure 5, overlaps with the historic intensity catalog from 1903 to 1921. Some events are clearly within the subducted lithosphere, others clearly within the overriding plate, and those within the fore arc are the most likely to have occurred along the plate interface. The terminations of the rupture zones of Sumatra's great earthquakes and the location of clusters of moderate and large events in the fore arc (Figures 5, 6a, and 6b) imply that seismic heterogeneities exist on the plate interface. The geology and geophysics of the fore arc and the structural fabric of the subducted plate indicate that "tectonic heterogeneities" also exist. The spatial coincidence of these features suggests a relationship between earthquake occurrence and tectonic features. The rupture process of great earthquakes is likely to be modified and sometimes terminated by these stress discontinuities.

Subducted Plate

The most shallow earthquakes (0-20 km) immediately adjacent to the Sunda trench are commonly associated with strain release occurring within the subducted lithosphere. Focal mechanism solutions for several earthquakes (C2, Fc13, K3, ISC, Mu4, Mu7) are consistent with the interpretation of these as normal faulting events associated with bending stresses in the flexing lithosphere at the outer rise (i.e., their T axes are perpendicular to strike of the trench). The 1977 Sumba earthquake is one example of a high stress drop, large normal faulting event located on the oceanic plate. The inversion for total moment ($M_o = 24 \times 10^{27}$ dyn cm) indicates that rupture during the main event was concentrated at a depth of 15 km in the more brittle part of the lithosphere [Silver and Jordan, 1983]; larger aftershocks occurred between 8 and 24 km [Fitch et al., 1981]. The 1921 earthquake (M_s = 7.5), also a large intraplate event, occurred seaward of the trench near the Roo Rise, an unusually thick piece of oceanic crust. The large magnitude of these two events, and the general appearance of more near-trench earthquakes by Java could indicate that here the gravitational force acting on the subducted Indian Ocean plate is likely to be substantial, since the slab is both very old and very long (Figures 3 and 7, and Cloetingh and Wortel [1985]). West of Sumatra, focal mechanism solutions for events occurring within the Indian Ocean Plate (L6, Fc65, WS) have nodal planes roughly parallel to the strike of fracture zones (Figure 7). Stein and Okal [1978] have interpreted the seismicity in the vicinity of the Ninetyeast Ridge as resulting from decoupling of the western half of this plate as it encounters resistance to the collision of India with Asia. This would result in left-lateral motion on north-south vertical fault planes, as is observed.

Overriding Plate

Epicentral locations of several large earthquakes display a distinct association with the Sumatra Fault System (1909, 1933, 1935, 1936, 1943(2), 1944). As the fault system enters the Andaman Basin, displacement occurs along the arc-parallel West Andaman Fault (Fc80) and transforms, which offset the Andaman Spreading Center (E4, Fc3, F4). Reverse faulting east of the islands (Mu9, Mu10, Mu11, Fb10) represents a compressive deviatoric stress regime [Mukhopadhyay, 1984].

Some interplate coupling must also occur by the Lesser Sunda Islands where compressional stresses within the upper plate are subparallel to the direction of convergence (as denoted by P axes of focal mechanisms: Fd6, K10, K11, K13, K5, K6, K7, Fc64, M16, M15). Habermann et al. [1986] investigated the relative levels of small ($m_b \geq 5.5$) shallow earthquake activity of the Sunda Arc and found an increase in activity in this area east of 116.4E. North of Timor, several large earthquakes beneath the volcanic arc (1930, 1952, 1953) occur in a region where the Australian continent is in the initial stages of collision with the arc. Reflection profiles north of the volcanic arc display a southward dipping thrust contact between the oceanic crust of the Banda Sea and overlying folded sediments [Silver et al., 1983]; thrust focal mechanisms (MN) with nodal planes parallel to this interface document what may be the early stages of a reversal in the polarity of subduction [McCaffrey and Nabelek, 1984; 1986].

ABE, magnitudes from Abe [1981]; B, surface wave magnitude determined in this study from station bulletins; (B), magnitude calculated from station bulletins; F, surface wave magnitude determined in this study from film chips; (GK), magnitude from Geller and Kanamori [1977]; GR, magnitudes from Gutenberg and Richter [1954]; (KA), magnitude from Kanamori and Abe [1979]; R, relocations done is this study; (R), magnitude and location (inaccurate) from Richter [1958]; dash indicates no magnitude available in Abe [1981]; M_sWSSN, surface wave magnitudes of Gutenberg and Richter [1954] and Abe [1981] corrected to WWSSN's M_s where the correction method is as determined by Perez and Scholz [1983]; M_sBSSA, surface wave magnitude from the Bulletin of the Seismological Society of America. This catalog overlaps with the historic intensity catalog from 1903 to 1921. The 1903 and 1907 epicenters are inconsistent with reported intensity patterns. The error ellipse representing the 99% confidence in location has a radii of 47-km latitude and 44-km longitude for the earlies (1921) relocated event only. Radii for all other events are less than 20 km; those for more recent events are substantially smaller. Depth control is poor due to the lack of nearby stations.

*Focal mechanism is presented in Table 1.

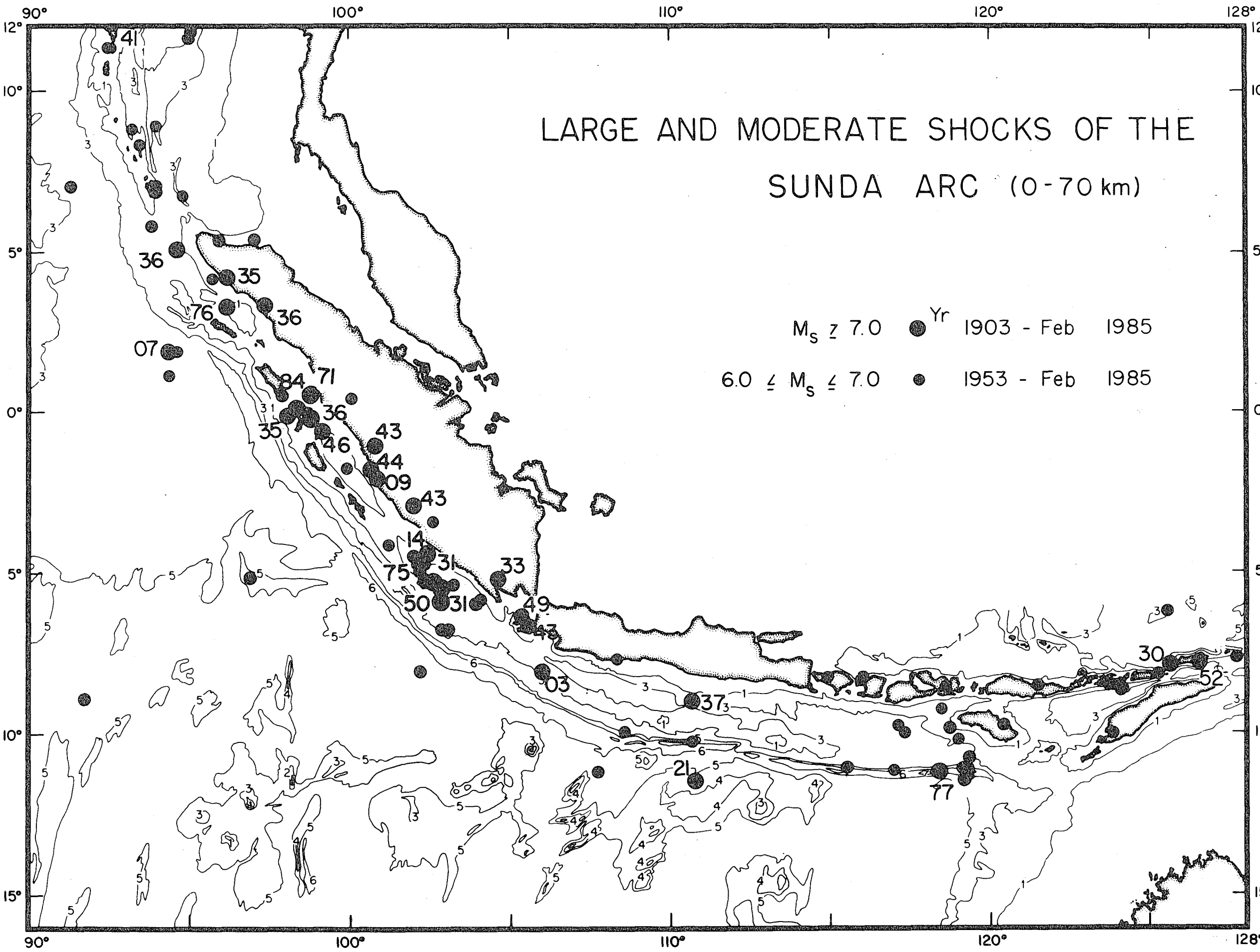

Fig. 5. Large shallow earthquakes ($M_S \geq 7.0$, $z \leq 70$ km) of this century are plotted with year indicated beside the epicentral location. All events since 1921 have been relocated (Table 2). Epicenters of the 1903 and 1907 events should not be considered to be accurate (see text). Moderate earthquakes ($6.0 \leq M_S \leq 7.0$) since 1953 are plotted. The catalog of large and moderate events was developed in this study.

Fore Arc of Sumatra

The majority of strong earthquakes in both the historic and instrumental catalogs of the Sunda Arc locate in the fore arc of Sumatra. While Nias and Enggano were documented as the locus of activity in the historic record, moderate and large instrumentally recorded earthquakes group principally in central Sumatra, on the Pini Arch, and in southern Sumatra, at Enggano. The region near Enggano has experienced a large earthquake every 27 years, on average, since 1756. Fault plane solutions for earthquakes in this region (Figure 2) are all thrust mechanisms at the appropriate depth of, and with one nodal plane coincident to, the plate interface. Large earthquakes occurred in central Sumatra, near the Pini Arch, during a major period of interplate and intraplate seismic strain release in the 1930's and early 1940's. The fault plane solutions and focal depths for earthquakes in this region (L7, L9, L11) are consistent with the interpretation of these events as plate interface events. Since the uneven distribution of seismic activity appears to be spatially stationary, it is likely to be intimately related to tectonic processes.

Northern Sumatra. The great earthquake of 1861, as defined by the lateral extent of maximum intensities, ruptured the entire arc segment between Banyak and Pini Islands. These islands lie on structural highs which are transverse to the strike of the arc and bound a sedimentary basin, defining a distinct block which has ruptured as a unit during great earthquakes. The Banyak Islands lie along a major cross structure associated with vertical faults (Figure 2), which have displaced fore arc basement in a right-lateral and vertical sense, representing a major break in the overriding plate [Karig et al., 1980]. It is likely that during a great earthquake such as the 1861 event, this structural discontinuity acts as a barrier and inhibits the propagation of rupture to neighboring regions. The lack of moderate and large earthquakes (Figure 5) and the lack of offset of stratigraphic horizons above these faults suggest that active deformation is absent and probably occurred prior to Pleistocene low stands of sea level [Beaudry, 1983].

At the southern boundary of the 1861 rupture zone, both the overriding and subducted plates exhibit tectonic features that are likely to effect the properties of the plate interface. Pini Island lies on a broad basement arch defined by structure contours of pre-Oligocene rocks [Karig et al., 1980]. The reduced rate of subsidence of this region, with respect to the remainder of the fore arc, has been attributed to this atypical basement structure [Beaudry, 1983]. Depositional facies suggest that stable platform conditions have existed since middle Miocene, significantly earlier than the remainder of the fore arc, implying that the Pini Arch is an anomalous crustal block within the fore arc.

The Investigator Fracture Zone (IFZ), the most prominent fracture zone east of the Ninetyeast Ridge, also intersects the fore arc at the southern boundary of the 1861 rupture zone (Figure 7). This fracture zone exhibits 1000-1500 m of relief, significant enough to have acted as a major sediment dam to along-strike sediment flow in the trench, and may be traced over 1700 km [McDonald, 1977]. The free-air gravity high associated with the IFZ continues into the fore arc, suggesting that this feature extends from the trench into the fore arc, and underneath the continental margin. The relief associated with the IFZ is likely to be flexurally compensated, as are other bathymetric features formed away from ridge crests, and not associated with a deep crustal root. The relief of

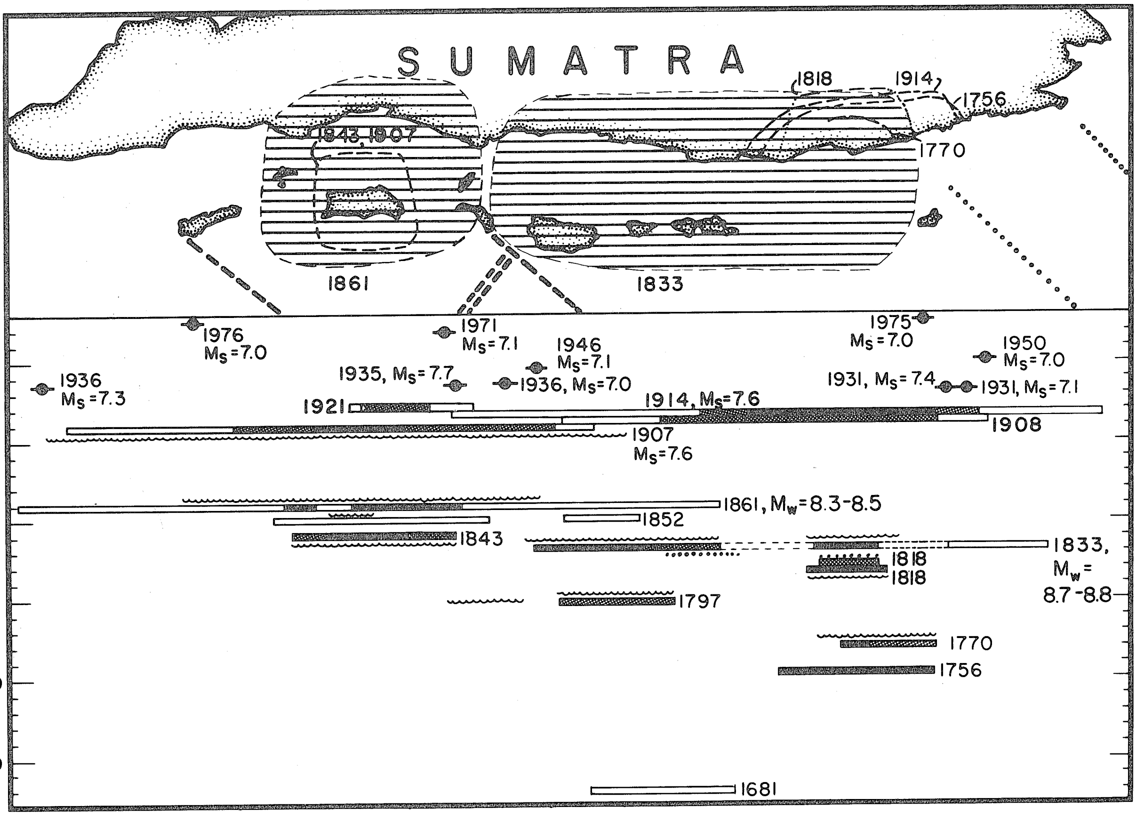

Fig. 6a. Rupture zones of historic earthquakes as delineated by intensity maps of Figures 4a, 4b, and 4c. Dashed lines are inferred extensions of fracture zones and a fossil spreading ridge into the forearc. Dotted lines are along-strike extensions of mapped troughs into the forearc as inferred from the seafloor fabric. By Java, the heavy horizontal line indicates the extent of the Roo Rise seaward of the trench.

the IFZ probably causes increased interplate coupling and an increase of intraplate stress and deformation, with respect to neighboring regions, in both plates.

The focal mechanism solution for the 1971 fore arc event (L8, M_s = 7.1, z = 40 km) is similar to those of nearby intraplate earthquakes occurring on the Indian Ocean plate. The depth, strike of nodal planes, and sense of motion associated with this event are inconsistent with both interplate displacement and the NW-SE oriented, right-lateral strike-slip displacement occurring within the upper plate. We propose that this earthquake is also occurring within the Indian Ocean plate along the

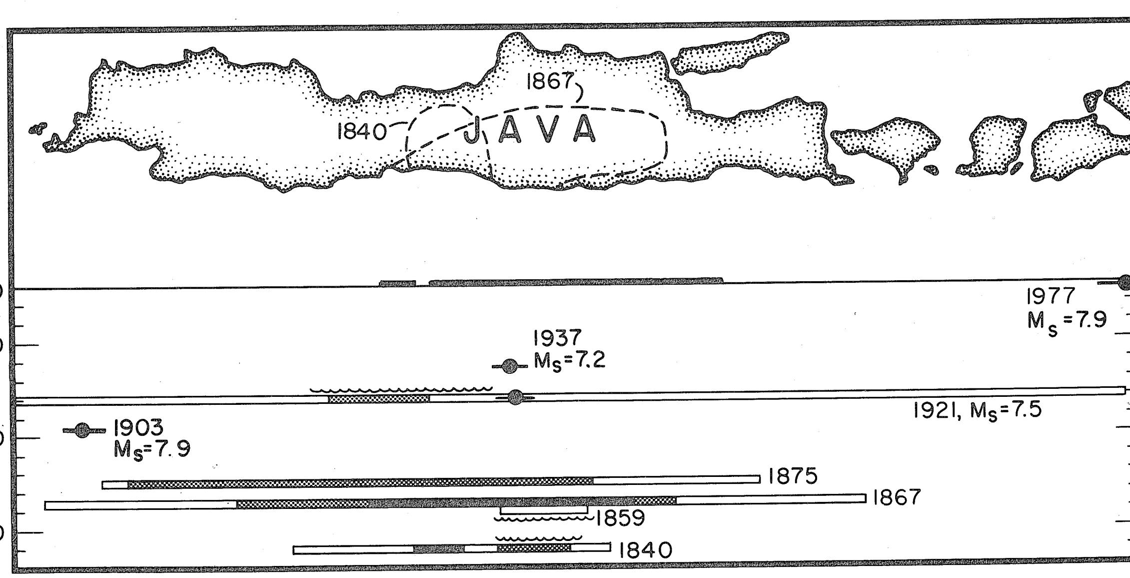

Fig. 6b. Space-time diagram summarizing the historic record (Figure 3) and the instrumental catalogs (Figure 4) developed in this paper Each horizontal bar represents one earthquake in the historic record. White indicates Modified Mercalli Intensity MM = I-IV, dotted: MM = V-VII, black: MM ≥ VIII. Wavy lines indicate the extent of the tsunami. Heavy dots indicate report of a seaquake. Epicenters of instrumentally recorded large shocks are plotted (with magnitudes).

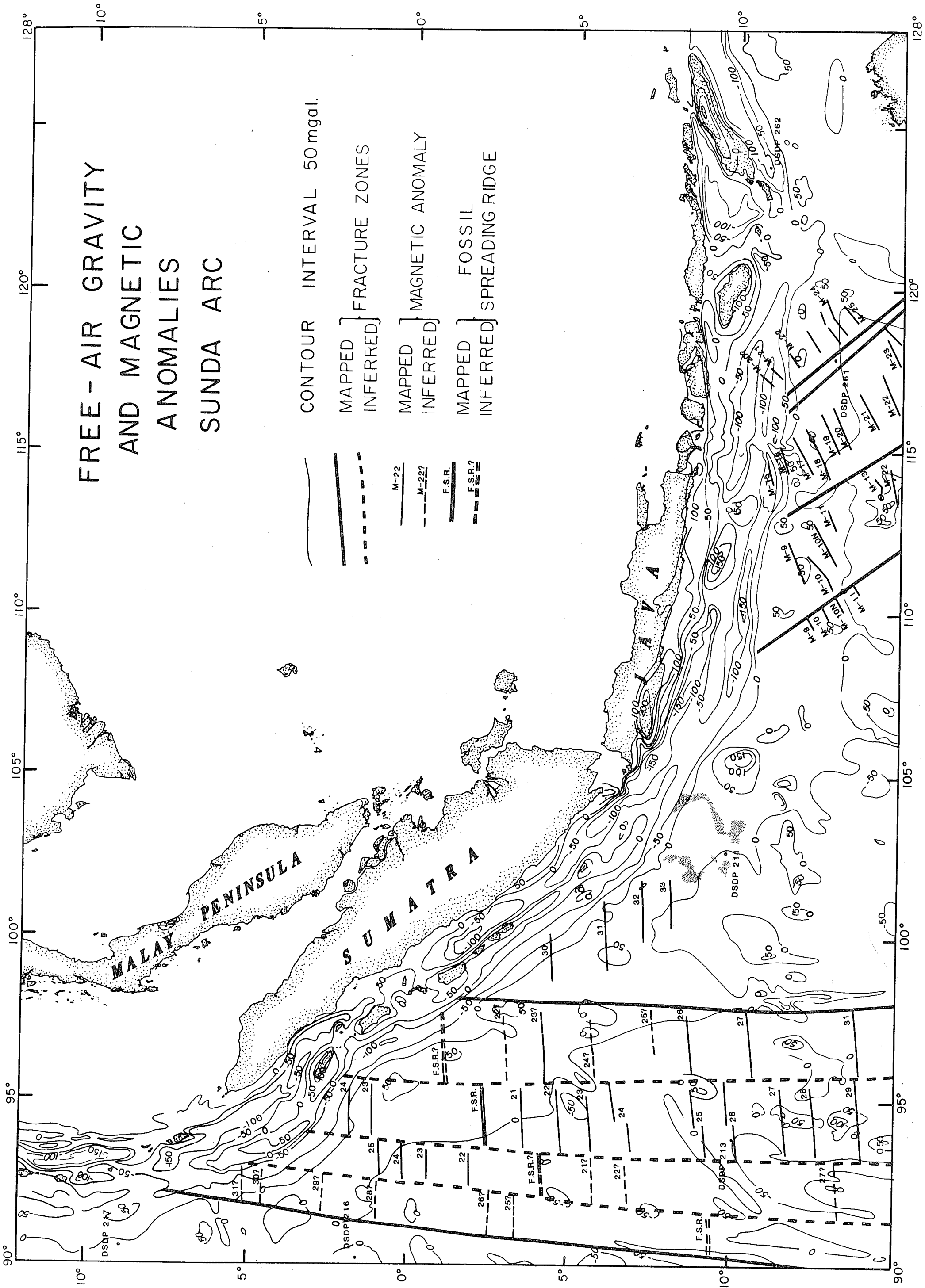

Fig. 7. Free-air gravity contours [Watts et al., 1978] and magnetic anomalies [Sclater and Fischer, 1974; Larson, 1975; Heirtzler et al., 1978; Liu et al., 1983] of the Sunda Arc. Lightly stippled areas seaward of the Sunda Strait are troughs with more than 600 m of sedimentary fill [McDonald, 1977] as discussed in text.

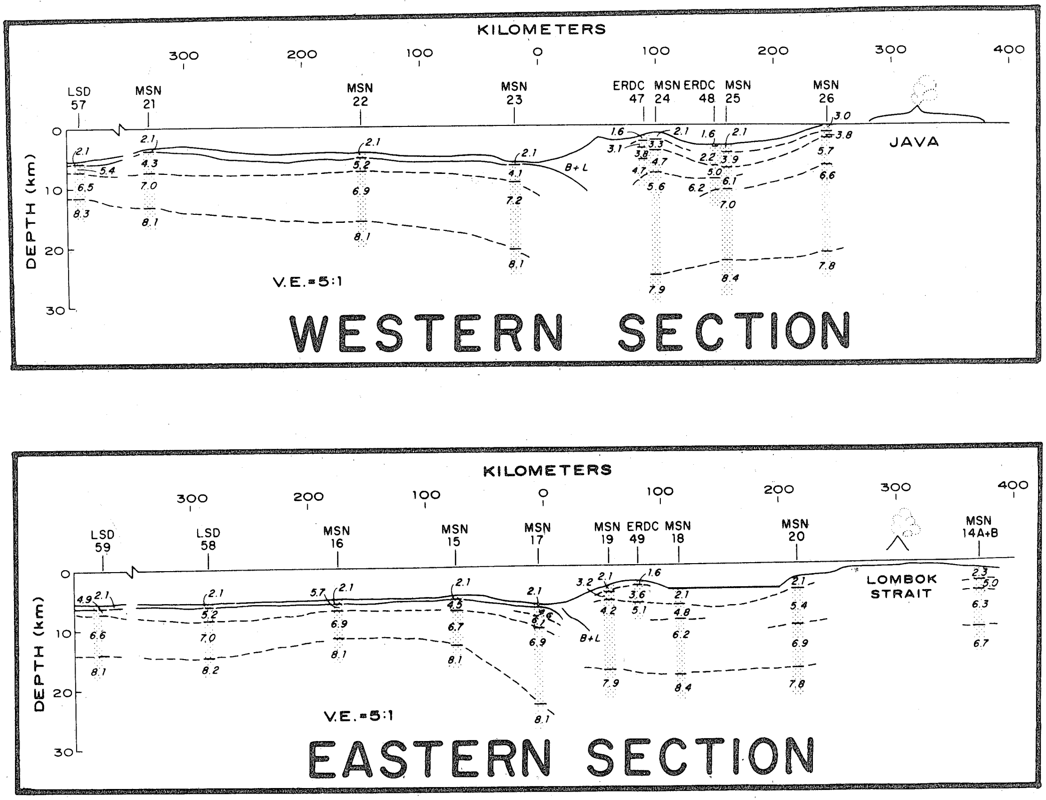

Fig. 8. Refraction profiles from Curray et al., [1977] indicate a thickened crustal layer nearer to the trench, which we interpret as the along-strike extension of the axis of the Roo Rise and another bathymetric high, features existing at the time of formation of this lithosphere (location Figure 1).

preexisting line of weakness represented by the IFZ. If this interpretation is correct, the slab pull force at this particular location, in contrast to Java, must be much less significant than the compression associated with collision of India and Asia; the slab is approximately 200 km long and 46 Ma at this location (Figure 3). It appears that these intraplate stresses are transmitted across the outer rise to depths of approximately 40 km within the subduction zone.

The fore arc in northern Sumatra near Simeulue has no recorded history of great earthquakes; however, it is structurally segmented as revealed by geology and seismology. The along-strike extension of the second most prominent bathymetric lineation east of the Ninetyeast Ridge, a fracture zone traceable over 900 km (Figure 7), also intersects the trench where it acts as a major sediment dam [McDonald, 1977]. This fracture zone is roughly coincident with the 1976 intraplate thrust earthquake (M_s = 7.0, z = 42 km, L4) and the northern boundary of the fore arc basin. While no cross structure is evident in the fore arc north of Simeulue, focal mechanism solutions and depths of two 1976 aftershocks (L5, z = 17 km; L3, z = 25 km) reveal active strike-slip faulting within the upper plate. Their nodal planes are consistent with right-lateral motion on splay faults which cross the fore arc, in a similar manner to the mapped splay faults farther east. It might be reasonable to assume that if the stresses acting on this portion of the plate margin are comparable to those on the 1861 rupture zone, the segment between the splay faults may also break during events similar in size to that of 1861.

Central and Southern Sumatra. The largest event discovered during this investigation occurred along the central and southern coast of Sumatra in 1833. High intensities were reported along 550 km of the coast from the Pini Arch (the southern boundary of the 1861 earthquake) to almost as far south as the island of Enggano. Clusters of moderate and large earthquakes near the ends of the highest intensity region, and the high level of recent small earthquakes at the southern end suggest that the 1833 event may have ruptured a large continuous block in the Sumatra fore arc extending from the Pini Islands to Enggano between two seismic discontinuities. The uniformity of the largest structural basin along Sumatra, the simplicity of fore arc free air anomalies (Figure 7), as well as the presence of large transverse features coincident with the ends of the basin also suggest a structural continuity to this arc segment.

At the southern boundary of the 1833 rupture zone a prominent discontinuity in the subducted plate exists. At 102.5E and 104.5E two large sediment-filled troughs intersect the trench (Figure 7) and separate crust of different ages. Seafloor to the east has no identifiable magnetic anomalies, being formed during the Cretaceous Magnetic Quiet Period; to the west, anomaly 33 (~80 Ma) has been identified. Presumably this trough is the expression of a fracture zone. Both troughs have at least 600 m of sediment fill, but the 102.5E trough has over 1.6 km of material at its maximum depth [McDonald, 1977; plates 1 and 2]. We infer that these features formed in crust of similar age and in an analogous position to the major grabens occurring along the southern end of the IFZ. Those features were "... probably generated in response to tensional forces in the crust induced by the change in spreading direction" [Larson et al., 1978] during the end of the Cretaceous Magnetic Quiet Period when a 55° rotation in spreading direction occurred, from the trend shown by Mesozoic anomalies south of Java to the north-south trend apparent in the seafloor west of Sumatra.

Instrumentally recorded earthquakes of this century (Figure 5) spatially group in two areas near the ends of the 1833 rupture zone. The northernmost group lies in the vicinity of the Pini Arch and is coincident with the along-strike extension of the IFZ. The southernmost cluster of moderate and large earthquakes, coincident with that observed in the historic record, is the most pronounced cluster of seismic activity in the Sunda Arc. Repeat times for eight of the nine large events occurring since 1756 are less than 25 years (Figure 6a). A longer, 81-year interval elapsed after the great earthquake of 1833, most likely since slip associated with this great earthquake relieved a large amount of strain energy at the plate boundary. Here, the along-strike extension of the 102.5E trough continues into the fore arc. A study of the relative level of small ($m_b \geq$ 5.5) earthquake activity indicates that this area near Enggano is also extremely active in the lower magnitude range [Habermann et al., 1986].

It is likely that the physical properties of the plate interface change where the grabens intersect the fore arc, representing a zone of rapid transition in interplate coupling. It is also likely that the high level of seismic activity in this region is caused by a prominent heterogeneity on the plate interface. Such regions may act as barriers to rupture during great earthquakes, as might be manifested by the southern termination of the region of highest intensities for the 1833 earthquake. From these data, we infer that this large segment of the Sumatra subduction zone may repeatedly rupture during great events with magnitudes near $8^1/_2$ to 9.

Sunda Strait. Between Enggano and the Sunda Strait seismic activity is more similar to Java (i.e., more aseismic) than Sumatra. An examination of relative levels of small earthquake activity [Habermann et al., 1986] reveals that this region (104.1E to 107.5E) is exceptionally quiet; in fact, it is the most quiet zone along the Sunda Arc. The only seismic activity is a cluster of moderate and large earthquakes immediately adjacent to the west coast of Java. Focal mechanisms (L18, L19) and focal depths for two events in the cluster are consistent with the interpretation of these events as interplate earthquakes.

Between Enggano and the Sunda Strait, both the fore arc and the subducted plate undergo transition. The age of the seafloor, the orientation of fracture zones, and the strike of the Benioff zone all change significantly (Figures 3 and 7). The morphology and gravity signature of the fore arc are not similar to adjoining regions in that there is a landward deflection of the trench axis and trench slope break, a pinching out of fore arc basins, and a seaward deflection of the fore arc gravity high (off of the axis of the trench slope break). The development of this region may be understood by considering the entire Sumatra margin as a discrete tectonic block [Curray et al., 1978]. This block is defined by the right-lateral Sumatra Fault System, which enters the fore arc in this region, and the trench. We interpret the landward deflection of structures in the fore arc to be along the trailing edge of a block of fore arc basement, which is being displaced northwest with respect to the Sundaland platform of Sumatra and western Java. This model predicts extension within the trailing edge of the upper plate; normal faults have been documented on the slope by Huchon and Le Pichon [1984]. The subducted plate appears to have a more shallow dip and greater radius of curvature, as inferred from the gravity signature. This may be interpreted as the result of less horizontal compression of the oceanic plate prior to subduction in the region where the upper plate is displaced. Decoupling of the plate interface between Enggano and the Sunda Strait is likely to severely limit the strain energy accumulating in this arc segment and the ability to produce great earthquakes.

Java Fore Arc

While Java experienced significant earthquakes in the nineteenth century, none are clearly major interplate or thrust events (Figures 5 and 6b). Some large shocks that have intensity patterns centered on the fore arc basin also have patterns following structural trends and either no tsunami and/or no high intensities. These characteristics are likely to indicate inland or deep earthquakes. Some large shocks generated tsunamis, but the 1921 and 1977 plate bending events indicate all are not necessarily interplate earthquakes. Other large shocks, having intensity patterns centered on the fore arc basin, have intensity patterns following structural trends and either no tsunami and/or no high intensities. These characteristics are likely to indicate inland or deep earthquakes. The epicentral distribution of large earthquakes of this century and moderate earthquakes since 1953 indicates a relative lack of shallow events (Figure 5). The only large event that clearly indicates deformation within the fore arc occurred in 1937 (M_s = 7.2). This shock is not of sufficient magnitude to accommodate significant interplate motion, however, implying that from Java to the Lesser Sunda Islands most, and perhaps all, strain release is being accommodated aseismically.

Geophysical data provide evidence for the present interaction of a prominent oceanic plateau on the subducted plate with the fore arc. The Roo Rise, commonly more than 2.5 km higher than the surrounding seafloor, is anomalously thickened crust shown in two refraction profiles perpendicular to the trench at central Java and Bali (Figure 8, location shown in Figure 1). The average thickness of the oceanic crust (layers 2 and 3) in the abyssal plain is about 7 km, while at 109.4E the edges of both the Roo Rise and another bathymetric high nearer the trench exhibit significantly thicker sections, averaging about 11.5 km with a maximum of about 14.4 km. The along-strike extension of the axis of the Roo Rise at the trench (at 115.3E) shows a crustal thickness of 16.4 km. The unusually thick layer has been interpreted as thrust faulting with a basal thrust plane possibly located at the base of the crust [Curray et al., 1977]. However, it is not necessary to invoke thickening caused by compressional tectonism. The free-air gravity signature of this region shows no departure from the normal outer rise gravity high associated with bending of the lithosphere. The anomalously thick crust indicated by seismic refraction data and the absence of a free-air expression of the relief of the Roo Rise suggest that this rise is a compensated feature supported by a low-density root, as are features formed on ridge crests. Anomalously thick oceanic crust, formed after continents have rifted, is found on many of the world's passive margins [Mutter et al., 1982]. Profiler records from the Atlantis II indicate that the characteristic layered igneous structures, wedge like convex reflectors dipping away from the continental margin, exist within the upper crust of the Roo Rise.

The Roo Rise continues into the trench, as is shown by the axis of the trench being deflected 50-60 km landward and the great thickness of crust there; it also appears to be interacting with the fore arc. In contrast to adjacent regions where fore arc basins show undisturbed sedimentary fill, profiler records across the fore arc basins of Java and the Lesser Sunda Islands indicate that there has been recent uplift of the trench slope break in an isolated region immediately landward of the Roo Rise. Four profiler records at approximately 109E, 113E, 114E, and 115E (Figure 9, location in Figure 1) show this transition. The trench slope break at 109E appears to have been more active in the past as indicated by the small compressional folds at depth in the basin strata; the shallowest strata of the basin are generally undisturbed and away from the trench slope break, deeper reflectors are only broadly warped. It is apparent in section 113E that the seaward margin of the basin is actively rising; basin strata that onlap the trench slope break are strongly tilted landward. The point of intersection of the along-strike extension of the Roo Rise with the fore arc is just reaching this longitude. At 114E the fore arc basin strata are discontinuous and have been severely disturbed. We interpret this section as having been most recently affected. Section 115E shows flat lying sediments in a relatively undisturbed fore arc basin.

Although the exact limits of the Roo Rise are not clear, the strike this feature and the evidence we have presented suggest that substantial parts of its northern flank have entered the trench. The low-density root of the Roo Rise should cause this bathymetric feature to be more buoyant than the surrounding seafloor and therefore more difficult to subduct. There is no evidence of the depth to which the Roo Rise penetrates into the thrust zone. If it is interacting with crystalline material of the overriding plate, the increased interplate coupling might be expected to cause enhanced seismic activity ($M_s \geq 6.0$) relative to adjacent areas subducting old abyssal plains. This is not the case. There are few moderate and large earthquakes that are clearly associated with deformation in the fore arc (and not in the subducted plate; the region between 104.1E and 116.4E is a prominent quiet zone for small ($m_b \geq 5.5$) events [Habermann et al., 1986]. This may imply that the Roo Rise is in only the initial stages of subduction. Other authors have reported a lack of moderate and large earthquake associated with the subduction of broad bathymetric highs [Vogt et al., 1976].

Mode of Subduction (Seismic versus Aseismic) and Seismic Potential

The seismic history of the Sunda Arc presented here establishes the existence of great ($M_s \geq 7\ ^3/_4$) and numerous large ($M_s \geq 7$) interplate earthquakes near Sumatra. There is little evidence to support the occurrence of such events near Java. This variation in mode of interplate motion (seismic vs. aseismic) spatially correlates with changes in tectonic style along the arc. In studies of Pacific arcs, several characteristics of earthquake activity have been related to specific subduction zone parameters; similar relationships exist for the Sunda Arc.

The maximum magnitude of great interplate earthquakes in Sumatra ($M_w = 8^1/_2$-9) contrasts sharply with that of interplate earthquakes in Java (M = 7.2). The variation in maximum magnitude of earthquakes in the world's subduction zones is similar to the variation in seismic slip rate [Ruff and Kanamori, 1980]. In regions that have great earthquakes, seismic slip rates are comparable to the rate of relative plate motion [Kanamori, 1977]. Sumatra's great earthquakes account for a majority of

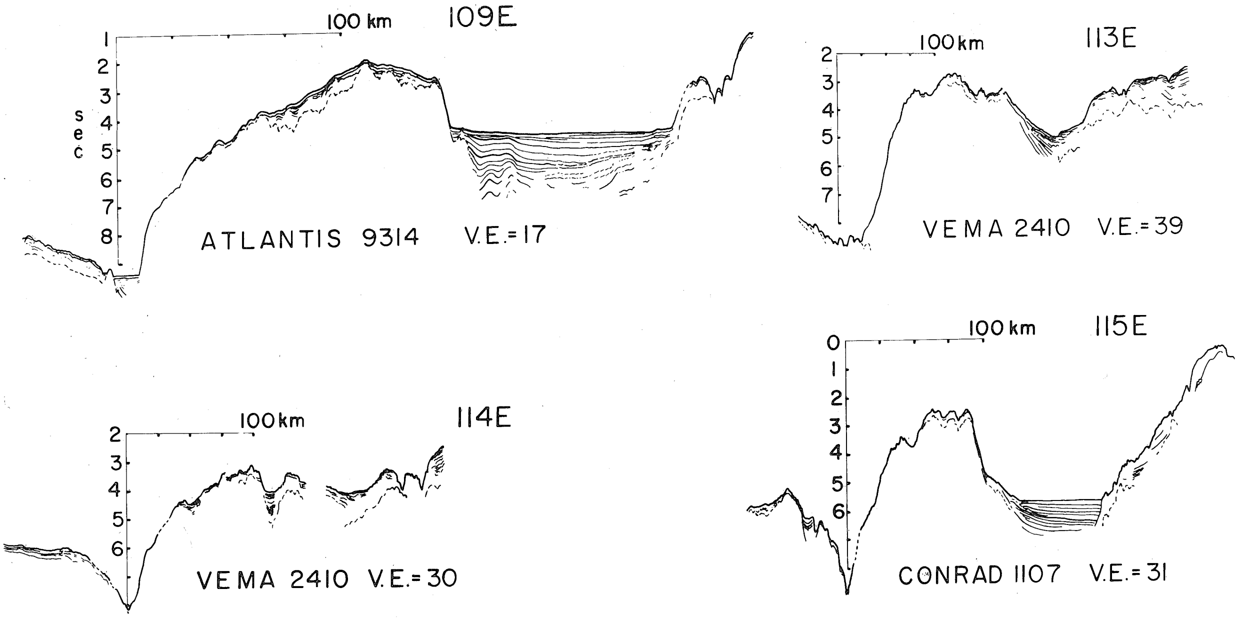

Fig. 9. Line drawings from four successive seismic profiles crossing the forearc south of Java at longitudes 109E, 113E, 114E, 115E (location Figure 1). Vertical scale is equivalent in all profiles; vertical exaggeration is indicated. Forearc basins at 109E and 115E are undisturbed. Profile at 113E shows progressively onlapping horizons implying recent uplift of the trench slope break. At 114E the forearc basin appears folded and faulted, indicating recent tectonism. Sites of disturbed forearc basins occur where the along-strike extension of the Roo Rise intersects the trench.

slip between the two plates. The lack of such events near Java indicates differential motion at the plate margin is principally being taken up aseismically or by small magnitude earthquakes.

A strong correlation of earthquake size with both age of the subducted lithosphere and convergence rate has been found [Ruff and Kanamori, 1983]. High convergence rates and subduction of younger seafloor are associated with regions of great thrust earthquakes, while regions with fewer such events tend to subduct older seafloor at low rates. Convergence rates along the Sunda Arc do not change substantially, but the difference in age of the subducted lithosphere is greater than 100 my (Figure 7). Mesozoic anomalies M-21 and M-22, entering the trench south of the Lesser Sunda Islands, indicate that 150-152 m.y. old crust [Berggren et al., 1984] is subducted there [Heirtzler et al., 1978]. The youngest seafloor, a fossil spreading center that became extinct after the formation of magnetic anomaly 20 (46 Ma, Berggren et al. [1984]), enters the trench near central Sumatra [Liu et al., 1984]. The basis for this correlation may be interpreted in terms of the subducted plate's trajectory, where convergence rate controls the horizontal component and slab age controls the vertical component [Ruff and Kanamori, 1983]. The average density of an oceanic plate increases as it ages, since more high-density mantle is underplated with time. The difference in vertical velocity upon subduction, causes changes in coupling along the plate boundary and hence changes in ability to generate great earthquakes.

In the Sunda Arc, the width of the plate interface, as measured from the trench axis to the 100-km depth contour, indicates a more broad zone of contact at Sumatra, where great interplate earthquakes occur, and a relatively narrower zone at Java, where shallow portions of the Benioff zone dip more steeply (Figure 2). The width of the zone of contact between adjoining plates has been related to the characteristic earthquake size of Pacific subduction zones [Kelleher et al., 1974]. Extremely long rupture zones (> 400 km), and hence great earthquakes, were found to occur at margins with shallowly dipping slabs and wide zones of contact, while moderately large rupture zones (> 150 km) occur in regions that dip more abruptly. These observations are consistent with the concepts of coupling in that younger lithosphere being subducted at a higher convergence rate has a more shallow dip, a greater area of contact, and greater shear traction applied to the plate boundary.

In the Sunda Arc, a gross correlation exists between the nature of the overriding plate and the occurrence of great earthquakes. Sumatra and

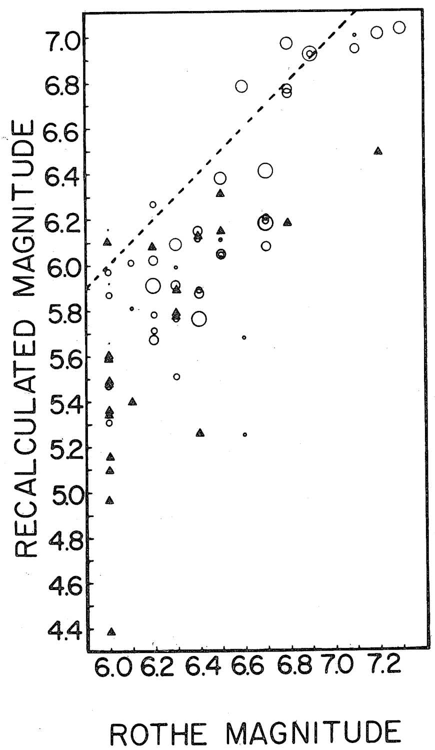

Fig. 10. Magnitude given by Rothe [1969] is plotted against the average surface wave magnitude determined in this study for events from 1953 to 1965. The circles denote the average of the station bulletins, their size indicates the number of stations used in the average (1 to 7). The triangles represent the average of magnitudes determined from film chips. The dashed line is where these two magnitudes are equal. Rothe consistently overestimates the magnitude of the vast majority of events. This is most pronounced at the lower magnitude range.

western Java are on a continental plate that includes most of Southeast Asia [Hamilton, 1979]. The region of transition to oceanic crust is represented by a Cretaceous melange terrane, extending from western Java into Borneo, and by the late Oligocene-early Miocene paleoshelf edge extending across central Java [Hamilton, 1979]. Progressive thinning of continental crust is also suggested by the decrease in $^{87}Sr/^{86}Sr$ ratios from western Java through Bali and the spectrum of high-potassium calcalkaline volcanics in Sumbawa [Hutchinson, 1982]. Strain energy release along most of the continental portion of the plate boundary occurs seismically, whereas the island arc of eastern Java and the Lesser Sunda Islands is relatively aseismic for great earthquakes. While no study has been done on this specific relationship, we note that in a list of earthquakes with the largest M_w [Kanamori, 1977, Table 2] of the 32 subduction zone related events, 25 occur where subduction takes place beneath a continental arc. Molnar and Atwater [1978] found a gross correlation between tectonic style of the overriding plate (Cordilleran tectonics versus interarc spreading) and age of the subducted plate. The theory describing this relationship predicts an increase in coupling between the plates where increased shear stress on the plate boundary imparts compressive stresses to the overriding plate [England and Wortel, 1980]. While earthquakes with P axes generally parallel to the direction of convergence occur within the upper plate throughout the arc, the continental arc of Sumatra and western Java has a higher concentration of intraplate activity. The island arc of eastern Java and the western Lesser Sunda Islands has less seismicity.

Conclusion

The great earthquakes in the historic record as well as instrumentally recorded events of this century demonstrate a remarkable spatial variation in occurrence along the Sunda Arc. The variation in age of the subducted seafloor correlates with the variation in mode of strain energy release, as reflected in the amount of seismic activity and the maximum magnitude of earthquakes, as well as the dip of the shallow portion of the Benioff zone. There are more frequent and larger earthquakes along Sumatra where younger, more shallowly dipping seafloor enters the trench, indicating a significant seismic slip rate; less frequent and smaller events occur along Java where subduction of older seafloor takes place relatively aseismically. The effect of variation in age is also reflected in the deeper portion of the Benioff zone where the similarly increasing dip and depth of penetration of the slab are more pronounced at Java. The Sunda Arc also appears to exhibit a gross correlation of maximum magnitude of earthquakes with the nature of the upper plate (continental versus oceanic).

The extent of rupture zones of the great "gap-filling" earthquakes in Sumatra (1833, $M_w = 8^3/_4$; 1861, $M_w = 8^1/_4$-$8^1/_2$), as defined by the span of maximum intensities (MM ≥ VIII), appears to be controlled by heterogeneities on the plate interface. The edges of the rupture zones may be delineated by structural features entering the trench and/or structures within the overriding plate; they are also identified as sites of enhanced seismic activity. Moderate and large earthquakes in these clusters have repeat times that are much shorter than the recurrence intervals for adjoining regions that broke only during the great earthquakes. It is possible that rupture propagation across these heterogeneities is inhibited and such locations are initial sites of rupture during great gap-filling earthquakes.

Characteristics of the Sunda Arc presented here and studies of the mode of strain energy release in Pacific arcs lead us to infer that the entire length of the plate boundary along Sumatra south to the island of Enggano has the potential to produce great thrust earthquakes. The seismic potential of the Sumatra coast should be considered high, category 1 of McCann et al. [1979], as the historic record clearly documents two great interplate shocks with more than 153 and 125 years having elapsed since their occurrence. No repeat times for these great events may presently be determined, since there is no recurrence of events of comparable magnitude during the length of the historic record presented here. In marked contrast, much or all of the plate margin along Java and the Lesser Sunda Islands east to the termination of the trench should be considered to have low seismic potential. Large interplate shocks are lacking along extensive segments of this part of the margin. Those large events in the historic record may not clearly be identified as thrust earthquakes.

Appendix: Development of a Homogeneous Earthquake Catalog

We have examined the catalog of moderate and large, shallow earthquakes ($M_s \geq 6.0$) for spatial variations of occurrence which, if observed over sufficiently long intervals of time, are likely to be related to regional tectonics. Temporal and spatial variations in the occurrence of events may either be real, reflecting changes in the earth, or they may be apparent, reflecting changes in detection, reporting, or method of determining magnitude [Habermann, 1981]. To accurately determine true spatial changes in seismicity, a catalog of events must be temporally homogeneous and consistent in magnitude. Problems with homogeneity may arise when combining data from standard earthquake catalogs [e.g., Gutenberg and Richter, 1954; Richter, 1958; Duda, 1965; and Rothe, 1969] which do not determine magnitude by the same method since such differences alone are significant enough to generate apparent changes in seismicity.

In this study of Indonesian earthquakes we wanted to ensure the true spatial distribution and magnitude of as lengthy a catalog as possible. The most readily determined parameter indicating relative size of shallow-focus earthquakes is the surface wave magnitude, M_s. Gutenberg and Richter's (1954) magnitudes are essentially equivalent to the modern definition of M_s [Geller and Kanamori, 1977], and their catalog is complete for large earthquakes ($M_s \geq 7.0$) from 1918 to 1952. We incorporated their catalog and relocated all events between 1921 and 1952 by the method of Bolt [1960] using P wave arrivals given by ISC (Table 2). For the years 1966 to February 1985, surface wave magnitudes of moderate and large earthquakes as reported by the Bulletin of the International Seismological Centre (ISC) and the Bulletin of the Seismological Society of America's (BSSA) Seismological Notes were included. Thirteen more years of moderate and large events (1953 to 1965) were added by using the catalog of Rothe [1969] however, our combined catalog is inhomogeneous due to different methods of determining magnitude. A homogeneous catalog of large earthquakes since the early part of this century and moderate and large earthquakes from 1953 to February 1985 was developed (Table 2) by recalculating the magnitudes of events occurring between 1953 and February 1985 (Table 3).

Determination of Magnitudes

Both the ISC and BSSA used the surface wave magnitude formula adopted by the International Association of Seismologists and Physicists of the Earth's Interior [Vanek et al., 1962]:

$$M = \log_{10}(A/T)_{max} + \log_{10}\Delta + 3.3$$

Rothe has a very inconsistent method of determing magnitude. He used magnitude values from Duda [1965] for events of magnitude 7 or greater. Duda used the revised magnitude, M, introduced by Richter [1958]:

$$M = {}^1/_4 M_s + {}^3/_4(1.59m_b - 3.97) \qquad z \leq 40\text{ km}$$

$$M = 1.59m_b - 3.97 \qquad 40 \leq z \leq 60\text{ km}$$

which heavily weights body wave magnitudes. For magnitudes less than 7, Rothe determines the magnitude in one of two ways.

1. He compares magnitudes given by different stations (he lists six, one of which, Uppsala, already incorporated its own station corrections), and attempts to establish linear equations which convert the magnitude determined at one station to that determined by another. He then averages these newly calculated values.

2. When station bulletins did not report magnitudes, Rothe estimates the magnitude from the number of stations that reported the earthquake by using a regression curve. Only the final result of these methods is recorded in his table.

We calculated surface wave magnitudes for more than 70 events, reported by Rothe as being magnitude 6 and larger, occurring along the Sunda Arc between 14N to 135E from 1953 to 1965. We used surface wave amplitudes as reported from station bulletins or read from film chips after the advent of World-Wide Standard Seismograph Network (WWSSN). We adopted the convention of Preliminary Determination of

Table 3. Recalculation of Rothe Magnitudes (1953-1965)

Date	Magnitude Rothe	Avg	WWSSN	PRA	RIV	UPP	KIR	TSK	LPH	BAA	LPB	TAC	CHH	VCM	MER
April 6, 1953	6.1	6.01		6.03		6.12			5.90						
May 18, 1953	6.0	5.97		5.97	6.06	5.40									
May 25, 1953	6.0	-													
June 25, 1953	6.9	6.92		7.27		6.88			6.62						
June 25, 1953	7.1	7.00			7.12	6.87									
June 26, 1953	6.8	6.77		7.03	7.04	6.65			6.36						
Aug. 17, 1953	6.0	5.66			5.66										
Nov. 7, 1953	6.0	5.92			5.92										
Nov. 13, 1953	6.3	5.99			6.19	5.79									
May 2, 1954	6.2	5.71		5.35	5.80						5.98				
June 6, 1954	6.8	6.97				6.97			6.93		6.83	7.02	7.08		
Oct. 14, 1954	6.5	6.11			6.39				5.83						
Nov. 2, 1954	6.6	6.78		6.88	6.77	6.67			6.70		6.86				
March 6, 1955	6.5	6.03			5.99						6.03				
March 22, 1955	7.1	6.94			7.45	6.70			6.58		7.02				
May 17, 1955	7.3	7.03		6.77	7.12	7.41			6.62		7.27				
May 29, 1955	6.5	6.38		6.10	6.68	6.32			6.23		6.57				
July 14, 1955	6.1	5.81			5.84	5.77									
Sept. 9, 1955	6.6	5.68			5.61	5.75									
Sept. 15, 1955	6.7	-													
Jan. 11, 1956	6.3	6.09			5.82	6.01	6.31		6.07		6.26				
April 2, 1956	6.5	6.04			5.94	6.13					6.19				
May 1, 1956	6.6	5.25				5.12	5.38								
Sept. 29, 1956	6.3	5.91			5.60	5.85	6.01				6.19				
Feb. 2, 1957	6.3	5.51			5.41	5.45	5.66								
March 11, 1957	6.4	6.11			6.05	6.03	6.25								
April 29, 1957	6.2	5.78			5.78	5.62	5.95								
May 12, 1957	6.7	6.21			6.29	5.93	6.42								
June 18, 1957	6.4	5.89			5.70	5.76	6.21								
June 18, 1957	6.7	6.08		5.74	5.90	6.12	6.57								
July 9, 1957	6.2	6.02			5.84	5.82	5.96				6.45				
Oct. 3, 1957	6.0	-													
Jan. 13, 1958	6.0	5.48			5.48	5.34	5.61								
June 25, 1958	6.9	6.92		6.90	7.58	7.14	6.88		6.77		6.65		6.67	6.78	
March 4, 1959	6.1	-													
April 6, 1959	6.5	6.05				6.18	6.12	5.78			6.11				
June 28, 1959	6.4	5.76		4.63	5.65	5.88	5.74		6.45		6.21				
Oct. 12, 1959	6.2	5.67			5.72	5.47	5.87	5.61							
Nov. 3, 1959	6.4	5.87		5.59	5.99	5.92	5.96								
Nov. 26, 1959	6.7	6.18		5.99	6.48	6.15	5.98	5.95			6.53				
Nov. 26, 1959	6.7	6.41		6.20	6.42	6.65	6.56	6.30			6.36				
Jan. 11, 1960	6.0	5.31			5.18	5.48	5.28								
June 15, 1960	6.0	6.16			6.16										
Oct. 7, 1960	6.8	6.75		6.55	7.03						6.65		6.78		
July 11, 1961	6.2	5.91		5.53	5.86	5.93	6.03	6.07			6.05				
Oct. 26, 1961	6.4	6.15			6.14	5.91	6.16				6.37				
Dec. 6, 1961	6.3	5.77				5.65	5.73	5.93							
May 15, 1962	7.2	7.01				7.08	7.11						7.04	7.05	6.78
Nov. 16, 1962	6.7	6.20			5.99	6.25	6.37								
Dec. 21, 1962	6.2	6.27			6.36	6.30	6.15								
Dec. 22, 1962	6.0	5.87			5.79	5.98	5.84								
March 24, 1963	6.2	6.30	6.08(46)		6.36	6.27	6.26								
March 25, 1963	6.4	5.39	5.26(31)		5.29	5.46	5.40	5.42							
March 31, 1963	6.0	5.10	4.97(12)				5.10								
May 18, 1963	6.0	5.60	5.35(45)		5.58	5.60	5.62								
May 22, 1963	6.0	5.82	5.60(52)		5.83	5.74	5.89								
Aug. 14, 1963	6.2	6.00	5.10(32)		6.00										
Oct. 24, 1963	6.3	5.86	5.79(67)		6.00	5.76	5.95	5.73							
Dec. 16, 1963	6.4	6.30	6.13(55)		6.23	6.16	6.50								
Dec. 16, 1963	6.0	-	4.39(16)												
April 23, 1964	7.2	6.83	6.49(79)			6.51	6.63	6.77				6.85	6.75	7.48	
June 13, 1964	6.0	5.36	5.16(05)			5.23	5.49								
June 15, 1964	6.0	6.24	6.10(75)			6.01	6.46								
July 28, 1964	6.5	6.42	6.15(75)			6.25	6.83	6.17							
Sept. 15, 1964	6.8	6.30	6.18(78)			6.15	6.31	6.44							
Sept. 16, 1964	6.3	5.79	5.89(65)			5.67	5.75	5.94							
Nov. 30, 1964	6.5	6.27	6.31(85)			6.09	6.05	6.67							
Feb. 18, 1965	6.0	-	5.36(29)												
Feb. 26, 1965	6.0	5.89	5.59(36)			5.68	6.09								
April 9, 1965	6.0	6.19	5.49(26)		6.19										
May 31, 1965	6.0	5.54	5.49(59)			5.49	5.58								
Aug. 17, 1965	6.3	6.13	5.79(53)			6.08	6.18								
Oct. 7, 1965	6.1	5.66	5.40(62)			5.59	5.73								

This table includes all shallow hypocenters in Rothe [1969] with M greater than 6.0 and their associated magnitudes. Avg. magnitude, the average surface wave magnitude as calculated from station bulletins listed. WWSSN magnitude is the average surface wave magnitude as calculated from WWSSN film chips, number of records in parentheses. Dash indicates no surface wave information is available in any bulletins consulted.

Epicenters (PDE) and BSSA and used the maximum amplitude of the vertical component in the period range 18 - 22 s. For stations with only horizontal seismometers, we adopted the ISC convention of determining the amplitude by using the root-mean-square of the north-south and east-west components to get a maximum horizontal amplitude:

$$A_H = (A_N^2 + A_E^2)^{1/2}$$

and the mean period. When several different amplitudes were given, the amplitude corresponding most closely to the 20 s period wave was chosen. Finally, all of the surface wave magnitudes from individual stations for each earthquake were averaged.

Results

The results of our calculations are plotted in Figure 10 and listed in Table 3. Our calculated surface wave magnitudes are plotted against Rothe's magnitudes. The dashed line represents Rothe's magnitude being equivalent to our average M_s value. The symbols represent magnitudes determined from station bulletins (circles with size corresponding to the number of stations reporting) and film chips (triangles).

Rothe consistently overestimated the magnitude of the vast majority of earthquakes in his catalog. In the magnitude range 6.8 and above, Rothe's magnitudes are generally 0.2 magnitude units higher. In the magnitude range 6.0 to 6.7, Rothe's magnitudes are generally overestimated by 0.4 to .05 magnitude units. This overestimation is most extreme at the lower magnitude range, suggesting that our catalog is complete for shocks $M_s \geq 6.0$. Rothe's catalog may be complete for events with magnitudes less than 6. We are now confident of having a homogeneous catalog for earthquakes $M_s \geq 6.0$ from 1953 to February 1985, which does not include the smaller events of Rothe that would give the previous catalog of combined events a significant bias and lead to spurious interpretations. The new homogeneous catalog is plotted in Figure 5 and listed in Tables 2 and 3.

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