SEISMIC ACTIVITY AROUND AND UNDER KRAKATAU VOLCANO, SUNDA ARC: CONSTRAINTS TO THE SOURCE REGION OF ISLAND ARC VOLCANICS

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ABSTRACT

There is general agreement that calc-alkaline volcanic rocks at convergent plate margins are genetically related to the process of subduction (Ringwood, 1974; Maaloe and Petersen, 1981; Hawkesworth et al., 1997). However, opinions on the mode and site of generation of primary magma for island arc volcanism differ substantially. The site of generation of calc-alkaline magma is thought to be either in the mantle wedge (Plank and Langmuir, 1988; McCulloch and Gamble, 1991) or in the subducting slab (White and Dupré, 1986; Defant and Drummond, 1990; Edwards et al., 1993; Ryan and Langmuir, 1993). We present seismological evidence in favour of the latter concept. A distinctive seismicity pattern around and under the Krakatau volcano was identified during systematic studies of the SE Asian convergent plate margins by means of global seismological data. A column-like cluster of events, probably associated with the dynamics of the volcano, is clearly separated from the events in the Wadati-Benioff zone. The accuracy of hypocentral determinations of the events of the cluster does not differ from the accuracy of the events belonging to the subducting slab. The depths of the cluster events vary from very shallow to about 100 km without any apparent discontinuity. On the other hand, there is a pronounced aseismic gap in the Wadati-Benioff zone directly beneath the volcano at depths between 100-150 km. The Krakatau cluster connects this aseismic gap to the volcano at the surface. The pervasive occurrence of earthquakes in the continental wedge between the subducting slab and the Earth surface bears witness to the brittle character of the continental lithosphere and casts doubt on the existence of large-scale melting of mantle material. The aseismic gap (Hanuš and Vaněk, 1985), interpreted by us as a partially melted domain occurring in subducted slabs in practically all active subduction zones that reach depths greater than 100 km, is here used as evidence for the location of the primary source region of island arc volcanics in the subducting plate.

Keywords: Krakatau, Sunda Strait seismicity, island arc volcanism, subduction, magma genesis, Wadati-Benioff zone, intermediate depth aseismic gap.

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1. INTRODUCTION

The Krakatau volcano (6.10° S, 105.42° E), well known for the catastrophic eruption in 1883, is situated in Indonesia in the Sunda Strait between Sumatra and Java (Fig. 1). The volcano belongs to the volcanic chain of the Sunda Arc, a zone of interaction between the subducting oceanic Indo-Australian plate and the continental Eurasian plate (*Hamilton, 1979*; *Simkin et al., 1981*; *Neumann van Padang, 1951*). Convergence between the two plates occurs in the NNE-SSW direction at a rate of 5 – 7.7 cm/yr (Plate Tectonic Map of the Circum-Pacific Region 1:10,000,000, south-west quadrant, 1986). The Sunda Arc changes direction substantially between Sumatra and Java; the direction of convergence is nearly orthogonal off Java and oblique off Sumatra. The Sunda Strait marks the zone of transition between these two different convergent geometries.

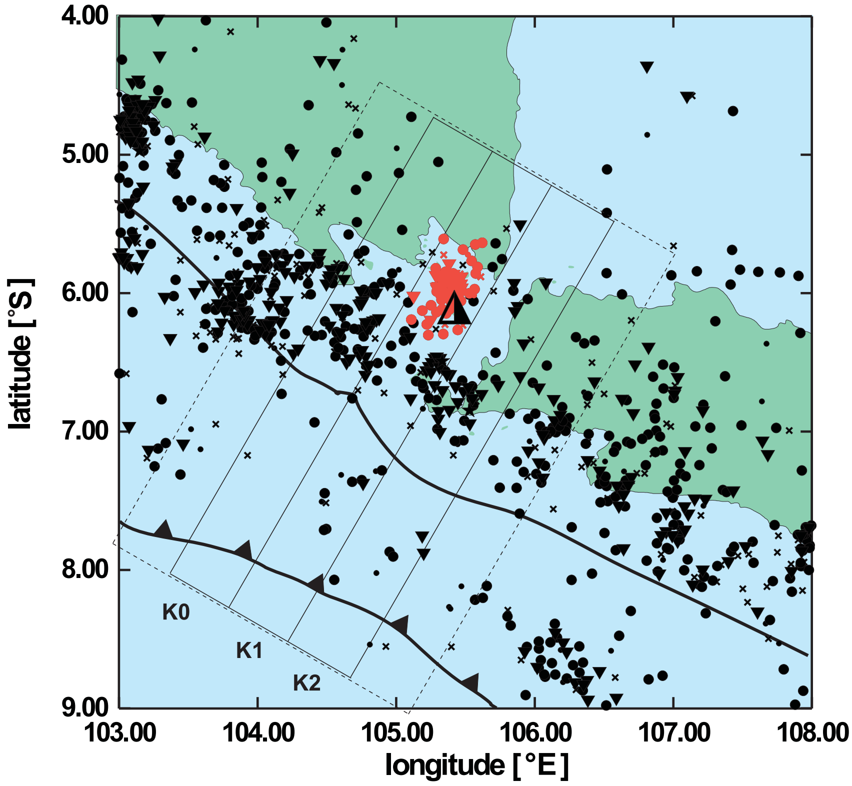

Fig. 1. Distribution of earthquakes in the Sunda Strait and vicinity. Symbols for earthquakes with ISC magnitude m_b: • $m_b \le 4.0$, × $4.0 < m_b \le 4.5$, ● $4.5 < m_b \le 5.0$, ▼ $5.0 < m_b \le 6.0$, ★ $m_b > 6.0$. Epicentres of earthquakes located in the Krakatau cluster K are denoted by grey symbols, the Java trench by a serrated line, the axis of the forearc basin by a heavy line, the positions of sections K0, K1 and K2 by rectangles, the area of the longitudinal section (Fig. 4) by a dashed rectangle, and the position of Krakatau volcano by a black-and-white triangle.

The Sunda Strait has been interpreted as a consequence of an extensional tectonic regime (*Pramumijoyo and Sebrier, 1991*). Extension is also indicated by the existence of the seismically active, SW trending, Selat Sunda fracture zone that forms the southern termination of the Great Sumatran fault zone (*Hanuš et al., 1996*). *Harjono et al. (1991)* suggested the presence of a fault at this location and with practically the same azimuth on the basis of the distribution of microearthquakes in the Sunda Strait.

A distinctive seismicity pattern around and under Krakatau volcano was found during our systematic studies of the SE Asian convergent plate margins by means of global seismological data. In these studies we have used hypocentral determinations of the International Seismological Centre (ISC) (Regional Catalogue of Earthquakes 1964-1999) as relocated by Engdahl et al. (1998), denoted as EHB relocations.

2. EARTHQUAKE DISTRIBUTION

The EHB data base contains events that are well-constrained teleseismically by arrival-times reported to ISC. Hypocentre determinations have been significantly improved and the uncertainty in focal depth estimates has decreased. The distribution of 1964 – 1999 earthquake epicentres of the published EHB data set in the Sunda Strait region is shown in Fig. 1 (for data see Appendix). To analyse seismic activity in such a seismotectonically complicated environment, narrow vertical cross-sections perpendicular to the main structural units of the region (trench, axis of fore-arc basin, coastal line, volcanic arc) have been used (*Hanuš et al., 1996*). The technique enables us to distinguish between the events belonging to the Wadati-Benioff zone and those situated in the overlying continental wedge, especially those belonging to the Krakatau cluster K (grey symbols). Three vertical cross-sections K0, K1, K2 around the Krakatau volcano with cross-section widths of 55 km and azimuths of 30° are shown in Fig. 2. Events belonging to the Krakatau cluster are clearly visible in section K1 and can be easily distinguished from those belonging to the Wadati-Benioff zone. At depths between 100 – 150 km, the Wadati-Benioff zone is characterised by a region without any strong teleseismically recorded events. Such a gap in seismic activity is usually well defined in the Wadati-Benioff zones of all convergent plate margins we have studied and is spatially correlated with active calc-alkaline volcanism (*Hanuš and Vaněk, 1985, 1988*; *Hanuš et al., 1996*; *Vaněk et al., 1987, 1994*). Its width laterally varies from a hardly distinguishable gap to tens of km. The absence of strong earthquakes seems to indicate that the slab loses its brittle character at these depths.

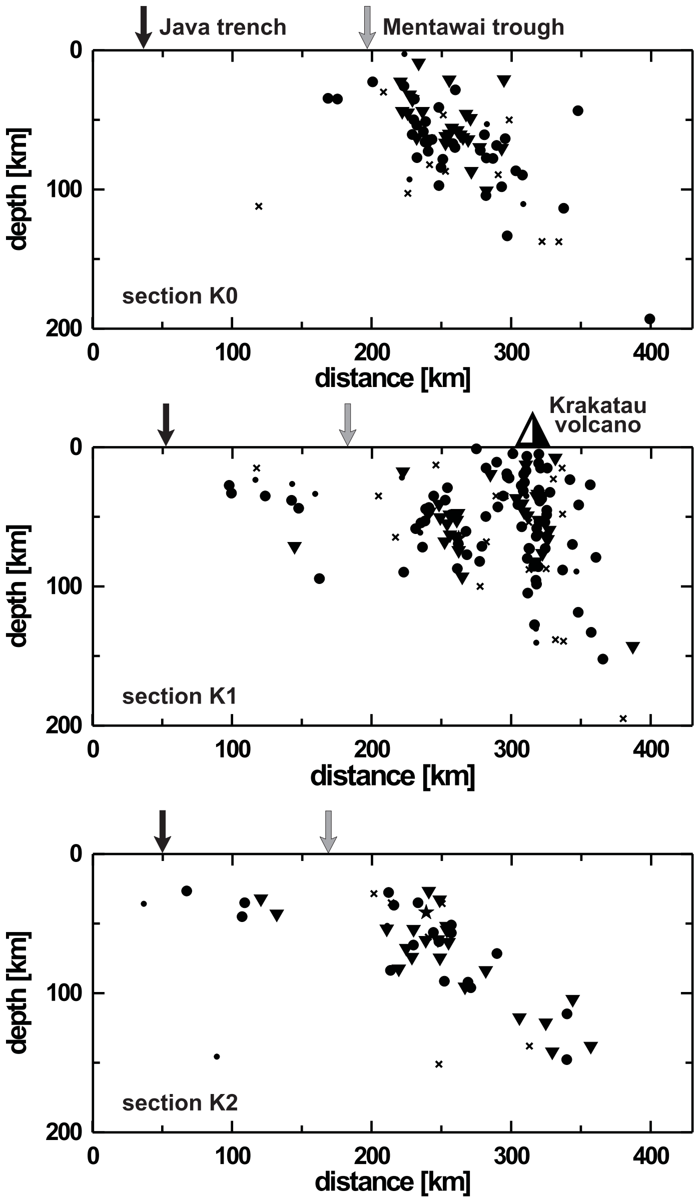

Fig. 2. Vertical cross sections K0, K1 and K2 perpendicular to the Java trench, giving the depth distribution of earthquake foci in relation to the position of the trench and the forearc basin. Section azimuth 30°, section width 55 km. See Fig. 1 for earthquake symbols and section locations.

3. ACCURACY OF EARTHQUAKE LOCATIONS

Special attention must be paid to the accuracy of EHB relocated parameters. The quality of estimates for individual events in the EHB data base is expressed by a simple classification system: DEQ – depth free solution, LEQ – depth fixed by program, FEQ – depth fixed by Engdahl, XEQ – poor solution, Z – no observations in the azimuth range greater than 180°. Because the reliability of earthquake location is very important for the separation of domains with earthquakes from those without earthquakes, the greatest weight was assigned to DEQ locations. XEQ, FEQ, LEQ and Z locations were examined, but eventually discarded.

The standard errors in the estimates of position and depth were then used to compare the reliability of the locations of events in the Wadati-Benioff zone with those in the Krakatau cluster. The results for DEQ events are given in Table 1. It can be seen that the standard errors in depth (δh) vary from 2 to 15 km for earthquakes situated both in the Krakatau cluster and in the Wadati-Benioff zone The standard errors of the epicentre position (δe) vary between 7 and 27 km for events in the Krakatau cluster and between 5 and 30 km for those in the Wadati-Benioff zone. The accuracy of the EHB locations in the Krakatau cluster is thus practically the same as in the Wadati-Benioff zone and the delimitation of these two groups of earthquakes in space is not distorted by different errors in the location of earthquake foci.

Table 1. Range of standard errors of EHB relocations for DEQ events in km (*N* – number of events, n – number of observations)

Domain	*N*	for depth (δh)		for position (δe)	
		all events	events with n>50	all events	events with n>50
K	26	2.4 – 14.5	2.4 – 13.5	6.6 – 26.9	6.6 – 18.1
K0	40	2.5 – 14.9	2.5 – 13.2	5.0 – 30.8	5.0 – 17.8
K1	33	2.0 – 14.0	2.0 – 14.0	4.4 – 26.9	4.4 – 17.9
K2	34	1.7 – 14.8	1.7 – 11.9	4.2 – 28.3	4.2 – 15.2

4. SHAPE OF THE WADATI-BENIOFF ZONE IN THE SUNDA STRAIT REGION AND THE KRAKATAU CLUSTER OF EARTHQUAKES

For examining the shape of the Wadati-Benioff zone only earthquakes with DEQ locations were used. In the resulting vertical sections (Fig. 3) the foci of individual earthquakes are plotted with corresponding standard errors δe and δh . The thickness of the Wadati-Benioff zone ranges from 40 to 65 km and its linear part, from a depth of 50 km (denoted by heavy lines in Fig. 3), dips at 40° to NE. The extent of the intermediate-depth aseismic gap in the Wadati-Benioff zone in the vicinity of Krakatau is shown by its projection on the plane of the upper boundary of the Wadati-Benioff zone (dip 40°, strike 120°) and denoted by shaded area in Fig. 4.

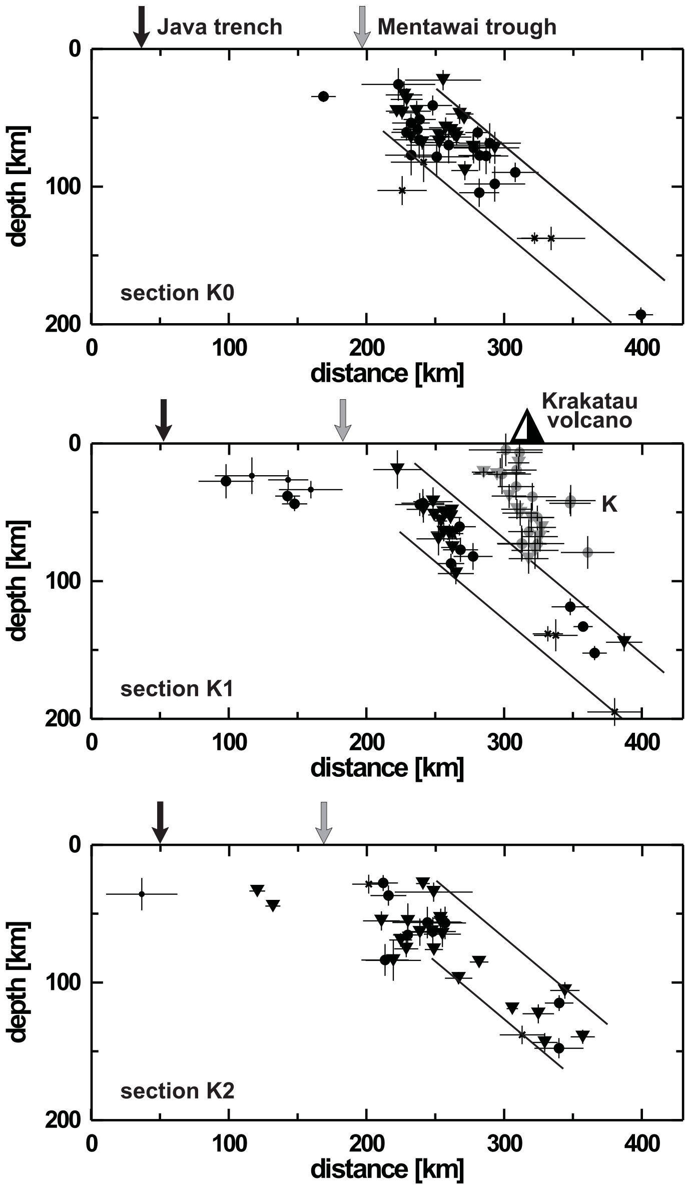

Fig. 3. Vertical cross sections K0, K1 and K2. Only events belonging to the Wadati-Benioff zone and classified as DEQ by *Engdahl et al. (1998)* are shown. In section K1, the DEQ events belonging to the Krakatau cluster K are also shown. Standard errors in position and in depth are denoted by bars. Section azimuth 30°, section width 55 km. See Fig. 1 for earthquake symbols and section locations.

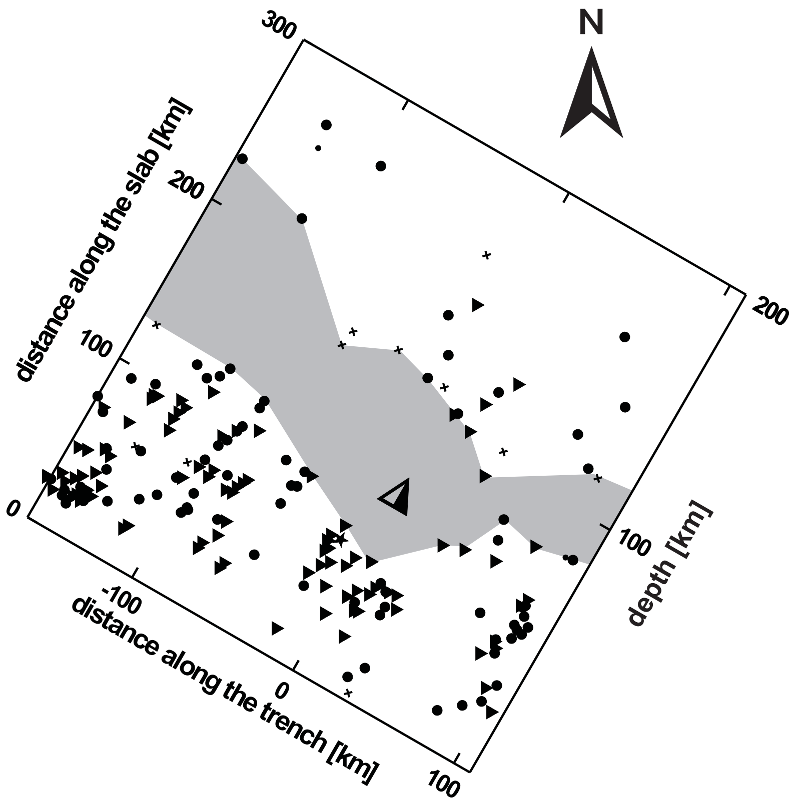

Fig. 4. Projection of the intermediate-depth aseismic gap (shaded area) and of DEQ events of the Wadati-Benioff zone on the plane of the subducting slab under Krakatau. Projected position of Krakatau is denoted by a black-and-white triangle. For position and orientation of the section and earthquake symbols see Fig. 1.

Detailed views of the locations of earthquake foci in the Krakatau cluster K are given in Figs. 5 and 6. The cluster consists of 77 events within the magnitude (m_b) range of 4.0 – 5.3 and is elongated in the SW-NE direction with the deepest earthquake at 105 km (Fig. 5). EHB locations for these events are listed in the Appendix. The maximum length in the SW-NE direction of the epicentral area of the K cluster is about 80 km and it is about 50 km across. Epicentres of a majority of the events belonging to the cluster (49 of the total of 77) are concentrated in a circular area with a diameter of 30 km. The Krakatau volcano is located on the southern edge of this circular area. The position and shape of the cluster is confirmed by the distribution of earthquakes with DEQ locations (26 events) shown in Fig. 6. Standard errors of DEQ locations are given for each event. The locations of the events of the Krakatau cluster have been determined to the same accuracy as the events in the Wadati-Benioff zone in the region around the Krakatau volcano (see Fig. 3 and Tab. 1).

Figures 2 and 3 and the vertical sections across the volcano in the S-N and W-E directions in Fig. 6 show an uninterrupted 'column' of earthquakes connecting the intermediate-depth aseismic gap in the Wadati-Benioff zone of the descending Indo-Australian plate with the Krakatau volcano. The earthquakes thus probably image the fractured magma conduit from the aseismic gap in the Wadati-Benioff zone through the continental lithosphere to the surface.

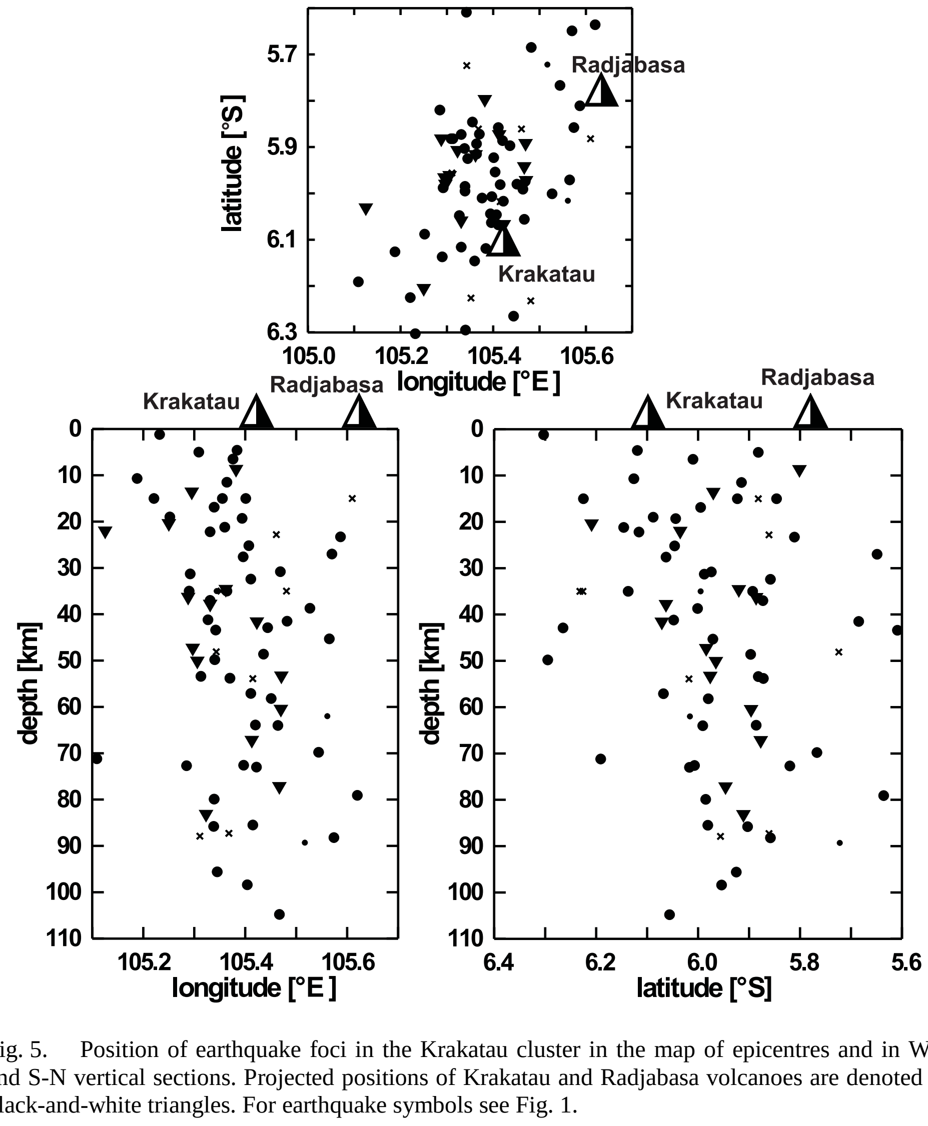

Fig. 5. Position of earthquake foci in the Krakatau cluster in the map of epicentres and in W-E and S-N vertical sections. Projected positions of Krakatau and Radjabasa volcanoes are denoted by black-and-white triangles. For earthquake symbols see Fig. 1.

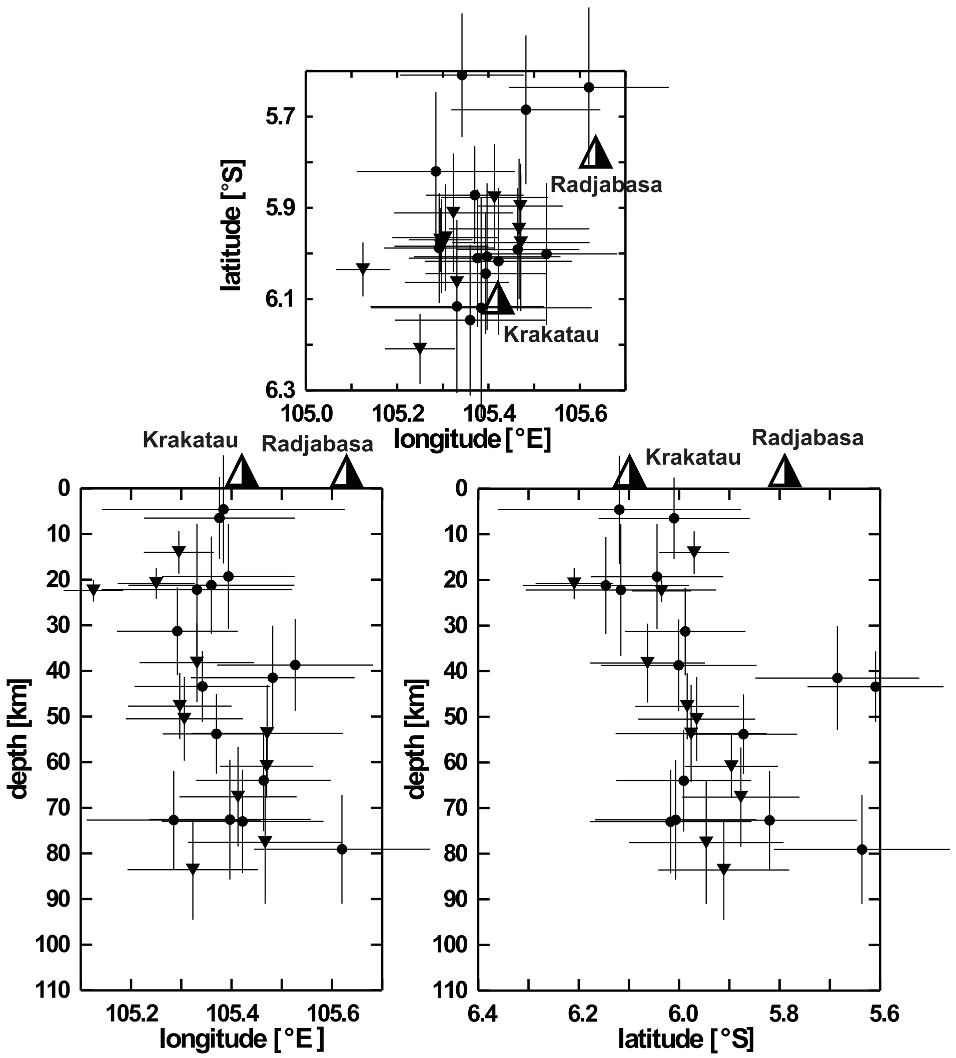

Fig. 6. Position of DEQ earthquake foci in the Krakatau cluster in the map of epicentres and in W-E and S-N vertical sections. Standard errors in position and in depth are denoted by bars. Projected positions of Krakatau and Radjabasa volcanoes are denoted by black-and-white triangles. For earthquake symbols see Fig. 1.

5. TIME OCCURRENCE, DEPTH VARIATIONS

Seismic activity in the Krakatau cluster in the last 36 years has been distributed uniformly through time (Fig. 7). Individual events for the period 1972 – 1999, which is covered both by the EHB hypocentral determinations and the *Smithsonian Institution (SI) Volcanic Activity Reports,* can be correlated with episodes of increased volcanic activity. The *SI Volcanic Activity Reports* contain 34 entries for this period, whereas the EHB database lists 52 hypocentral determinations for the same time interval. The only event common to both databases occurred on February 13, 1988. The EHB parameters for this event were m_b 5.1, depth 61 km (ISC depth 56 km). At the same time, felt earthquakes were reported in the SI. The implication of this low degree of correlation is that volcanic activity of Krakatau, corresponding to periods when magma reaches the surface and/or shallow subsurface levels, is not generally accompanied by strong, teleseismically recorded earthquakes. The earthquakes that form the Krakatau cluster thus reflect deeper tectonic processes related to magma ascent from the magmatic source region to the surface.

Figure 7 shows the variation in time of the focal depths of events in the Krakatau cluster. Despite the errors in depth determination, a clear pattern emerges. From 1964 the focal depths gradually increased from very shallow levels to events at depths close to 100 km. The deepest activity occurred in 1982 – 83. Later, between 1990 – 93, seismic activity under Krakatau moved rapidly to shallow depths of around 20 km. From 1993 up to the present, the depth of hypocentres has varied between 5 – 50 km, as was the case in

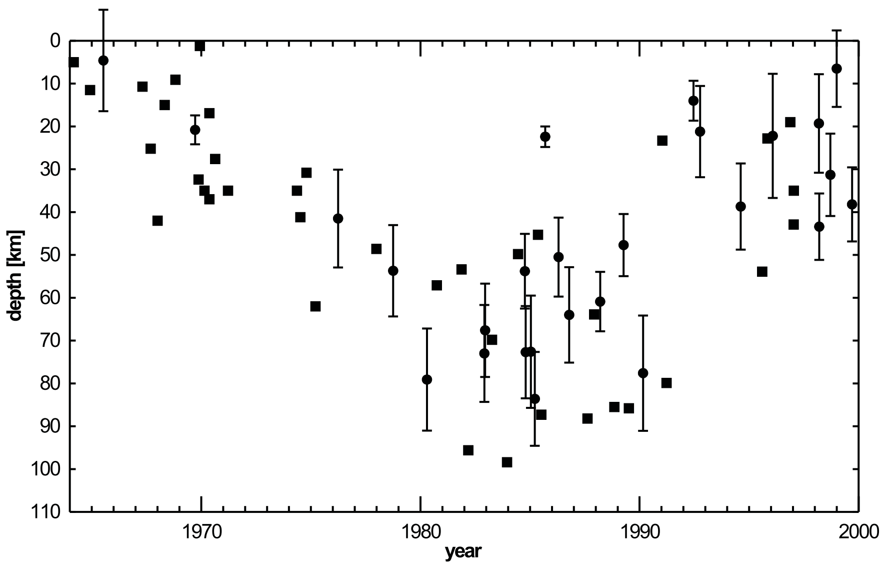

Fig. 7. Variation in time of the focal depths of earthquakes of the Krakatau cluster. Foci of DEQ earthquakes with standard errors in depth (*Engdahl et al., 1998*) are denoted by circles with bars, foci of LEQ earthquakes, for which errors in depth are not determined, by squares.

the period 1964 – 71. This pattern suggests that the release of seismic energy in the conduit may proceed in cycles from shallow crustal regions down to the upper boundary of the Wadati-Benioff zone. The duration of a single cycle seems to be about 30 years. This is comparable with the period of repetition (30 – 45 years) of the most intensive lava- and tephra-producing eruptions of the Krakatau volcano, which occurred in 1883 – 84, 1927 – 30, 1958 – 63, 1988 – 93 (*Simkin et al., 1981*; *Neumann van Padang, 1951*; *SI Volcanic Activity Reports*). However, the time span covered by reliable and homogeneous earthquake databases is too short for definitive conclusions. Only observations in the next 5 – 10 years will show whether the pattern of gradual focal depth increase is confirmed.

The relatively slow migration of seismic activity, from shallow subsurface levels down to 100 km depth in about 25 years, can be easily traced in Fig. 7. This process seems to be in disagreement with the intuitive idea of magma continuously ascending from the deep source region to the surface. It is difficult to explain such an obvious paradox and, unfortunately, no focal mechanisms for any of the events in the Krakatau cluster are listed in the Harvard centroid moment tensor solution database for the period from 1976 to the present to help us to constrain the limits of the geodynamic phenomena under the volcano. We can thus only speculate that during a series of strong explosive eruptions (e.g., in 1958 – 63), the magma extruded at the surface liberates space for the ascent of magma from deeper regions. This process progresses downwards, triggering relatively strong earthquakes. After some time interval (evidently about 25 years in the case of Krakatau), all the feeder channels beneath the volcano are filled with magma. From this point onwards the continuing generation of magma at depth and its tendency to ascend towards the surface provide the conditions for the next strong eruption. The final phase of the cycle is accompanied by a relatively fast migration of earthquakes towards shallow depth.

6. CONSTRAINTS TO THE POSITION OF THE SOURCE REGION OF ISLAND ARC VOLCANISM

The occurrence of intermediate to strong earthquakes beneath the Krakatau volcano and in its general vicinity provides new evidence relating to the problem of the source region of island arc magmas (*Poli and Schmidt, 1995*; *Macpherson and Hall, 1999*). The available petrological and chemical analyses of the volcanic rocks (*Neumann van Padang, 1951*; *Nishimura et al., 1980*; *Nishimura et al., 1986*; *Whitford, 1975*) indicate that Krakatau, despite its distinctive location and history of catastrophic eruptions, is a fairly typical island arc volcano. The types of lava ejected have varied between basalt and highly acid andesites (*Neumann van Padang, 1951*), with a wider range of chemical compositions than other Indonesian island arc volcanics (*Nishimura et al., 1980*; *Nishimura et al., 1986*; *Whitford et al., 1979*; *Nichols et al., 1980*; *Foden and Varne, 1980*). The continuous zone of relatively intense seismic activity extending from the upper boundary of the subducting slab at the depth of 100 km beneath the volcano to the volcano itself witnesses to the brittle character of the rock masses in this depth range of the continental lithosphere. This observation strongly constrains the possible site of generation of the primary magma.

Many authors have claimed that melts originate primarily in the mantle wedge above the subduction zone as a consequence of volatiles ascending from the subduction zone and lowering the mantle solidus (*Ringwood, 1974*; *Plank and Langmuir, 1988*; *McCulloch and*

Gamble, 1991; *Mc Kenzie and O'Nions, 1998*; *Aizawa et al., 1999*; *de Hoog et al., 2001*). This interpretation is based on hypothetical mathematical models of temperature distribution and metamorphic processes in the subducting slab (*Davies and Stevenson, 1992*; *Furukawa, 1993*; *Kirby et al., 1996*). However, if such a melting process were in operation in the mantle just above the subducting slab, the ductile character of the material would not permit faulting sufficient to generate magnitude 5 earthquakes. The occurrence of earthquakes of this magnitude in this region indicates that the mantle material above the slab below Krakatau is brittle; this fact casts doubt on the existence of large-scale melting of the mantle material in the lithospheric wedge above the subducting slab.

The pattern of seismicity around and below Krakatau thus indicates that the primary magmas of island-arc volcanoes probably originate within the subducting slab when material penetrates below 100 km. This interpretation is supported by the existence of the intermediate-depth aseismic gap (*Hanuš and Vaněk, 1985*) in the slab (compare Figs. 2, 3, 4) and is compatible with conclusions drawn in many recent geochemical papers (*Maaloe and Petersen, 1981*; *Hawkesworth et al., 1997*; *White and Dupré, 1986*; *Defant and Drummond, 1990*; *Edwards et al., 1993*; *Ryan and Langmuir, 1993*; *Shimoda et al., 1998*; *Prouteau et al., 1999*; *Yogodzinski et al., 2001*). The composition of the volcanic rocks extruded at the surface is undoubtedly influenced, to a greater or lesser degree, by the passage of the magma through the mantle wedge of the overlying continental lithosphere.

7. CONCLUSIONS

The almost columnar pattern of occurrence of relatively strong, teleseismically recorded earthquakes under the Krakatau volcano is a phenomenon that has not yet been observed beneath any other volcano at convergent plate margins. Geometrically, this seismically active domain is sharply delimitated and clearly separated both from the Wadati-Benioff zone of the subducting Indo-Australian plate and the subduction related fracture zones in the surrounding continental lithosphere. The accuracy of the determinations of earthquake foci of the Krakatau cluster, including the focal depths, does not differ significantly from the accuracy of hypocentre determination for events in the Wadati-Benioff zone in this region. The existence of an uninterrupted column of earthquakes down to the upper boundary of the subducting slab at a depth of 100 km is evidence for the brittle character of lithosphere over the whole of this depth range in the Krakatau region. Strong seismic activity could not be generated in the ductile environment represented by melted rocks.

The earthquakes in the Krakatau cluster are explained here by the specific stress and tectonic conditions rather than by the process of magma ascent. We suppose the seismotectonic behaviour of the continental wedge below Krakatau to be related to the bending of the Sunda Arc in the Sunda Strait area. This distinct bend of the margin of the Euroasian plate, where normal subduction under Java changes into oblique subduction under Sumatra, must generate local tectonic stress concentration in the continental wedge. The contribution of such local stress probably shifts the overall state of stress to a level only slightly below the stress necessary to overcome the strength of the rock in the area. The stress disturbances caused by the melts advancing towards the surface may serve as triggers of earthquakes in the subcritically stressed rock mass which has, moreover, been intensively fractured during the millions of years lasting transport of magma through the lithospheric wedge in this particular area.

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APPENDIX: EHB RELOCATIONS OF EARTHQUAKES IN THE KRAKATAU REGION (INDONESIA)

Krakatau - domain K - events around and under the volcano

type	yr	mon	day	hr	min	glat	glon	depth	mb	ntot	ser
LEQ	64	2	4	22	52	-5.882	105.309	5	5	29	17.51
LEQ	64	11	2	9	18	-5.915	105.364	11.5	4.9	19	16.35
DEQ	65	6	12	17	54	-6.119	105.384	4.6	4.9	36	26.86
XEQ	65	11	22	2	50	-5.649	105.57	27	4.7	18	45.7
FEQ	66	6	7	22	18	-5.846	105.355	15	5	43	12.5
LEQ	67	3	24	1	56	-6.126	105.188	10.7	4.9	34	14.68
LEQ	67	8	8	9	47	-6.046	105.407	25.2	4.6	20	21.76
LEQ	67	12	1	16	36	-6.071	105.423	42	5.1	38	16.4
LEQ	68	3	30	14	20	-5.882	105.61	15	4.5	16	26.36
LEQ	68	9	26	8	6	-5.801	105.382	9.1	5.2	36	11.19
FEQ	69	5	17	8	36	-5.893	105.364	35	4.6	28	14.95
DEQ	69	8	19	1	39	-6.209	105.25	20.8	5.1	110	8.54
LEQ	69	10	15	21	8	-5.858	105.411	32.4	4.7	21	21.52
LEQ	69	11	7	4	30	-6.303	105.232	1.2	4.6	23	12.68
LEQ	70	1	23	5	8	-6.226	105.352	35	4.2	17	32.38
LEQ	70	4	14	7	47	-5.995	105.339	16.9	4.8	35	15.27
LEQ	70	4	14	8	27	-5.873	105.331	37	5	44	14.01
LEQ	70	7	19	15	30	-6.063	105.396	27.6	4.9	37	15.52
LEQ	71	2	19	14	25	-5.92	105.362	35	5.1	54	16.48
FEQ	71	7	4	19	2	-5.886	105.288	36.7	5.2	59	11.5
FEQ	72	9	28	9	0	-5.923	105.401	15	5	31	13.16
LEQ	74	4	12	11	30	-5.995	105.344	35	0	17	19.02
LEQ	74	6	8	10	35	-6.048	105.327	41.2	4.9	35	13.36
LEQ	74	9	19	19	21	-5.974	105.469	30.8	4.8	28	14.4
LEQ	75	2	17	10	24	-6.016	105.561	62	0	21	33.22
DEQ	76	2	28	0	12	-5.685	105.482	41.5	5	52	18.11
LEQ	77	11	28	6	12	-5.897	105.436	48.6	5	30	23.62
DEQ	78	9	2	7	39	-5.976	105.471	53.7	5.2	67	16.7
FEQ	79	5	27	10	44	-6.056	105.467	104.8	4.9	58	11.81
XEQ	79	6	11	7	56	-5.956	105.311	87.9	4.3	24	35.28
DEQ	80	3	18	23	35	-5.636	105.62	79.1	4.6	36	19.46
LEQ	80	8	30	7	58	-6.068	105.411	57.1	4.7	48	12.71
LEQ	81	10	16	6	35	-5.882	105.313	53.4	4.7	17	33.52
LEQ	82	2	6	3	29	-5.925	105.345	95.6	4.9	67	12.18
DEQ	82	10	31	22	17	-6.017	105.422	73	4.6	50	17.89
DEQ	82	11	13	10	21	-5.877	105.413	67.6	5.1	154	12.96
LEQ	83	3	6	11	21	-5.767	105.544	69.8	4.8	64	12.09
LEQ	83	11	13	3	48	-5.954	105.404	98.4	4.8	73	13.01
XEQ	84	2	29	23	46	-5.724	105.343	48.1	4.3	13	65.95
LEQ	84	5	14	3	13	-6.295	105.34	49.8	4.8	16	23.97
DEQ	84	9	6	11	45	-5.872	105.37	53.8	5	128	11.88
DEQ	84	9	20	17	38	-5.82	105.285	72.7	4.8	35	19.27
DEQ	84	12	15	5	10	-6.007	105.397	72.6	4.9	66	17.85

DEQ	85	2	20	20	21	-5.911	105.323	83.6	5.1	115	14.46
LEQ	85	4	12	21	5	-5.971	105.565	45.3	4.8	45	14.63
LEQ	85	6	6	14	40	-5.861	105.368	87.3	4.5	17	28.11
DEQM	85	8	10	4	12	-6.035	105.125	22.4	5.3	210	6.57
DEQ	86	3	20	21	0	-5.965	105.306	50.5	5.1	139	12.95
DEQ	86	9	14	3	38	-5.991	105.464	64	4.9	113	14.91
ZXEQ	87	3	2	22	34	-6.191	105.109	71.2	4.9	17	40.31
LEQ	87	7	15	8	15	-5.858	105.574	88.2	4.7	18	18.72
LEQ	87	11	5	22	47	-5.886	105.42	63.9	4.8	44	15.33
DEQ	88	2	13	17	48	-5.896	105.47	60.9	5.1	93	10.31
LEQ	88	10	6	11	59	-5.981	105.415	85.5	4.7	50	10.81
DEQ	89	3	8	8	22	-5.984	105.297	47.7	5.1	109	11.45
LEQ	89	6	5	20	0	-5.903	105.338	85.8	4.7	41	15.71
DEQ	90	1	28	3	58	-5.946	105.467	77.6	5.3	125	17.09
LEQ	90	12	15	2	55	-5.811	105.587	23.3	4.7	17	34.8
LEQ	91	2	24	16	19	-5.985	105.339	79.9	4.6	34	17.75
ZFEQ	92	1	9	21	25	-6.225	105.221	15	4.7	34	16.3
DEQ	92	5	16	21	30	-5.97	105.295	14	5.1	177	7.76
DEQ	92	9	4	16	34	-6.146	105.36	21.2	4.8	46	18.35
DEQ	94	7	12	22	40	-6.001	105.527	38.7	4.8	88	17.24
LEQ	95	7	6	11	43	-6.018	105.415	53.9	4.5	40	12.54
ZDEQ	95	10	1	16	17	-5.722	105.517	89.3	4	17	22.86
LEQ	95	10	1	16	17	-5.861	105.461	22.8	4.5	15	14.19
DEQ	95	12	29	20	12	-6.116	105.331	22.2	4.7	44	21.07
LEQ	96	10	17	13	58	-6.088	105.252	19	4.6	53	12.03
LEQM	96	12	13	20	33	-6.265	105.444	42.9	4.7	65	10.3
LEQ	96	12	14	2	10	-6.232	105.481	35	4.5	46	14.83
FEQ	97	1	10	18	32	-5.98	105.451	58.2	4.7	127	8.79
FEQ	97	11	11	17	42	-6.137	105.29	35	4.8	79	11.23
DEQ	98	2	6	21	55	-6.044	105.394	19.3	5	60	14.66
DEQ	98	2	12	15	46	-5.609	105.342	43.4	4.9	47	15.02
DEQ	98	8	15	3	30	-5.988	105.292	31.3	5	82	13.35
DEQ	98	11	29	22	17	-6.01	105.376	6.5	5	50	16.71
DEQ	99	8	11	15	28	-6.063	105.331	38.2	5.1	74	12.68

Krakatau - section K0 - events in the Wadati-Benioff zone

type	yr	mon	day	hr	min	glat	glon	depth	mb	ntot	ser
LEQ	64	4	26	13	59	-6.086	104.75	65.5	5.7	85	10.51
DEQ	64	6	10	19	48	-6.225	104.78	57.2	5.7	58	12.03
DEQ	64	10	18	23	52	-5.944	104.938	71.8	5.1	40	17.73
DEQ	65	8	9	10	7	-5.997	104.744	71.2	5.2	27	17.51
DEQ	65	8	30	18	9	-6.487	104.664	46.3	5.5	68	9.3
LEQ	66	6	22	15	45	-6.702	104.723	30	4.4	13	32.2
LEQ	67	2	26	2	56	-6.297	104.595	65	5.2	31	12.39
DEQ	69	1	3	19	10	-6.239	104.636	41	4.8	27	13.99
ZXEQ	69	7	10	4	31	-5.992	104.828	53.1	0	12	46.95
ZLEQ	70	2	12	5	35	-6.122	104.568	61.5	5.2	17	24.78
LEQ	70	5	8	12	7	-6.472	104.78	10.5	5.1	21	14.85

LEQ	72	2	5	13	55	-6.605	104.776	24.1	5.1	47	13.87
DEQ	72	7	29	17	14	-6.01	104.775	71.9	4.8	51	14.58
DEQ	72	10	31	23	24	-6.197	104.876	64	5.6	64	10.84
LEQ	72	11	5	11	35	-6.581	104.784	2.7	0	20	13.68
DEQ	72	11	7	18	21	-6.25	104.518	67.9	5.1	109	8.3
DEQ	73	9	27	23	4	-5.986	104.811	77.4	4.9	50	15.35
LEQ	73	12	16	1	47	-6.28	104.57	72.5	5	26	19.4
DEQ	77	2	27	8	30	-6.427	104.752	45.2	5.4	138	10.26
DEQ	77	11	17	17	18	-6.092	104.734	47.2	5.4	145	10.08
DEQ	78	10	5	11	46	-5.921	104.897	98	4.9	26	22.19
DEQ	79	3	8	12	34	-6.318	104.602	51.2	5	51	11.77
DEQ	79	4	7	1	26	-6.175	104.612	68	5.2	58	14.52
DEQ	79	12	22	22	1	-6.206	104.857	62	5.2	116	8.32
LEQ	82	10	11	16	21	-5.831	105.019	110.5	3.8	17	28.84
LEQ	84	2	28	5	13	-5.927	104.953	63.5	4.9	51	16.47
DEQ	84	2	28	12	55	-6.068	105.086	68.4	4.7	42	22.68
LEQ	84	3	14	15	0	-6.009	105.004	89.4	4.4	31	18.21
DEQ	84	9	7	7	30	-6.008	104.844	104.4	5	64	14.57
LEQ	84	9	24	9	40	-5.543	105.043	113.5	4.8	29	17.96
FEQ	84	12	27	6	18	-6.175	104.612	86.9	4.4	18	21.54
DEQ	85	1	19	0	3	-6.356	104.554	53.7	5	39	13.65
ZLEQ	85	2	11	8	25	-6.258	104.697	84.2	4.9	25	23.47
DEQ	85	9	9	10	36	-5.955	104.842	77.7	5	60	16.21
ZLEQ	86	4	22	21	25	-6.204	104.486	64.1	4.8	51	12.83
LEQ	87	2	21	12	55	-5.858	104.971	86.6	4.8	37	19.48
DEQ	87	2	26	12	16	-6.067	104.758	88.3	5.1	99	9.79
DEQM	87	8	10	18	15	-6.214	104.833	59	5.4	191	6.05
ZDEQ	87	9	3	8	33	-6.262	104.811	22.6	5.1	15	27.59
DEQ	88	3	2	9	28	-6.461	104.735	64.1	5.4	144	7.36
ZLEQ	88	8	2	21	53	-6.728	104.173	35	4.7	18	22.68
DEQ	89	1	28	15	34	-6.263	104.729	78.3	4.7	30	23.6
LEQ	89	9	18	18	4	-5.954	105.026	133.3	4.8	28	17.8
DEQ	89	12	15	13	39	-6.309	104.413	60.5	5	56	10.88
DEQ	90	3	12	6	43	-6.313	104.587	65.9	4.8	41	19.21
LEQ	90	7	19	11	27	-6.01	104.855	102.3	5.1	37	12.37
ZDEQ	91	1	23	1	47	-6.456	104.562	25.7	4.8	19	26.78
DEQM	91	6	21	6	45	-6.07	104.754	50.3	5.5	236	5.02
DEQ	91	7	10	14	7	-6.128	104.653	69.8	4.6	20	30.83
XEQ	91	8	19	5	58	-6.117	104.638	28.4	4.7	13	38.53
DEQ	92	2	11	18	9	-5.052	105.304	193	4.6	106	8.93
DEQ	92	6	29	5	25	-6.405	104.723	58.4	4.7	57	17.76
DEQ	92	10	23	16	6	-5.975	104.767	60.7	5	87	9.09
DEQ	92	12	7	22	50	-6.934	104.41	34.5	4.9	56	8.97
LEQ	93	3	13	15	12	-6.216	104.778	67	4.7	15	24.86
ZLEQ	94	8	31	12	18	-6.313	104.765	97.2	5	22	27.06
DEQM	94	10	4	12	9	-6.276	104.79	63.2	5.6	134	7.34
ZLEQ	95	9	30	14	37	-6.533	104.767	92.8	3.9	16	30.2
DEQ	95	10	2	3	6	-6.236	104.512	82.2	4.4	30	23.84

DEQ	95	10	14	10	7	-5.705	105.26	137.6	4.2	14	24.88
LEQ	96	3	26	9	16	-6.328	104.848	46.5	4.5	47	13.4
DEQ	96	10	18	7	6	-6.302	104.463	77.1	4.6	42	18.94
FEQ	96	10	19	21	9	-6.395	104.583	49.9	5	70	10.19
FEQ	97	2	20	9	49	-5.778	104.746	50	4.4	26	19.94
FEQ	97	8	11	12	36	-6.412	104.619	35	4.6	48	12.77
DEQ	97	11	25	1	44	-5.791	105.193	137.4	4.4	58	9.59
DEQM	98	5	24	2	24	-6.543	104.787	33.3	5.1	89	13.3
DEQM	98	5	24	2	32	-6.533	104.804	36.6	5.2	104	11.62
LEQ	98	6	2	20	32	-6.76	104.683	22.7	4.7	38	10.93
DEQ	98	6	14	1	36	-5.693	104.77	89.6	4.8	20	17.02
DEQ	99	1	8	9	2	-6.423	104.554	102.8	4.3	21	17.94
DEQM	99	2	1	16	35	-6.514	104.641	45.2	5.2	66	7.86
ZXEQ	99	4	7	17	1	-7.172	103.927	112.1	4.2	13	42.76

Krakatau - section K1 - events in the Wadati-Benioff zone

type	yr	mon	day	hr	min	glat	glon	depth	mb	ntot	ser
DEQ	67	10	2	17	24	-6.573	105.218	42.2	5.1	49	14.27
DEQ	68	7	24	9	21	-5.797	105.481	139.3	4.3	33	15.94
DEQ	71	5	4	2	4	-6.547	105.312	49.9	5.9	227	6.64
LEQ	71	9	7	1	57	-6.835	105.192	21.8	0	13	22.08
DEQ	72	6	15	11	52	-6.514	105.257	64.2	5.2	91	9.52
DEQ	72	8	6	11	12	-6.542	105.237	69.2	5.1	62	16.05
LEQ	72	11	26	0	49	-6.38	104.964	38	4.9	18	14.39
LEQ	73	7	4	23	38	-7.386	104.76	72.5	5.2	48	10.95
ZLEQ	73	7	5	16	29	-7.28	104.897	94.4	4.6	27	16.79
DEQ	74	2	24	19	7	-6.216	105.124	82	4.8	65	14.17
DEQ	74	5	2	13	8	-6.483	105.276	65.4	5.1	86	10.18
DEQ	74	5	9	23	56	-7.286	104.853	33.5	0	23	23.15
DEQ	74	5	11	2	24	-7.363	104.682	38.2	4.9	95	9.03
DEQ	74	5	12	8	58	-7.313	104.603	26.4	0	27	14.61
DEQ	74	5	12	11	25	-7.506	104.462	23.4	0	11	26.86
DEQ	74	11	9	19	10	-6.492	105.332	65.3	6.1	284	4.56
DEQ	75	3	29	17	55	-7.35	104.751	43.8	4.9	74	9.19
LEQ	75	6	6	20	41	-6.507	104.967	46.6	5	39	13.78
DEQ	78	4	28	19	31	-5.519	105.895	144.3	5.2	44	13.2
LEQ	78	8	6	20	21	-6.758	105.235	58.5	4.8	20	16.57
DEQ	78	12	20	13	2	-6.68	105.278	47.8	5.4	102	12.21
LEQ	80	4	30	23	2	-6.685	105.197	71.8	4.8	26	21.54
LEQ	82	3	25	5	19	-6.26	105.287	68	4.3	24	20.45
DEQ	83	4	26	12	38	-6.487	105.299	53.7	5.2	115	8.1
ZLEQ	84	1	10	10	27	-7.515	104.493	15	4.3	15	26.47
DEQM	84	3	15	3	22	-6.583	105.252	51.9	5.4	277	4.41
ZDEQ	84	6	26	8	58	-7.704	104.495	33	4.6	33	14.92
DEQM	85	3	22	14	42	-6.599	105.367	56.3	5.9	358	4.47
ZLEQ	85	4	28	21	47	-6.631	104.861	89.7	4.6	21	22.52
LEQ	85	8	12	0	52	-6.058	105.558	127.5	4.7	11	31.08
DEQ	85	12	9	11	58	-5.64	105.717	152.2	5	122	8.87

DEQ	86	8	27	18	36	-6.276	105.063	77.2	5	55	12.75
LEQ	86	10	20	23	53	-6.636	105.144	53	4.7	35	12.05
DEQM	87	5	16	13	6	-6.484	105.317	75.5	5.1	134	8.19
XEQ	88	4	1	8	49	-6.721	104.912	64.7	4.2	16	44.36
DEQ	89	11	3	8	33	-6.332	105.1	94.5	5.1	49	13.07
DEQM	90	4	6	5	47	-6.776	105.104	18.9	5.6	105	17.45
DEQ	90	7	15	7	26	-6.495	104.951	43.3	4.8	68	15.58
DEQM	90	8	2	15	3	-6.474	105.293	48.8	5.4	315	4.51
DEQ	92	3	7	2	4	-6.281	105.059	60.4	4.9	84	11.88
DEQ	92	10	7	10	0	-6.656	105.188	44.3	4.9	29	17.9
DEQ	93	5	22	0	51	-7.711	104.479	27.4	4.7	25	19.95
ZXEQ	94	12	9	11	13	-7.445	104.484	35	4.9	11	41.51
LEQ	95	2	6	16	27	-6.48	105.304	69.3	4.9	39	10.63
LEQ	95	3	6	18	6	-5.977	105.441	140.4	3.9	17	23.2
DEQM	95	4	5	8	47	-6.343	105.055	87.2	5	114	9.7
FEQ	95	7	9	1	21	-6.548	105.105	35	4.6	20	13.59
LEQ	96	3	14	15	6	-6.573	105.177	12.8	4.2	16	13.7
DEQ	96	4	22	22	52	-5.985	105.703	138.2	4.5	52	11.04
LEQ	96	12	18	20	32	-6.564	105.355	48.4	4.6	38	15.14
ZFEQ	97	1	9	7	27	-6.205	105.111	100	4.3	31	20.12
FEQ	97	3	19	7	25	-6.958	105.103	35	4.3	26	11.84
FEQ	97	4	25	1	9	-6.461	105.132	29.1	4.7	77	6.43
FEQ	97	7	24	16	0	-6.718	105.226	61.4	4	19	13.58
DEQ	97	10	11	3	3	-5.754	105.764	133	4.7	96	7
LEQ	98	4	1	18	15	-6.505	104.866	54.3	4.6	24	28.69
LEQ	98	6	13	1	8	-6.026	105.52	130.4	4	14	26.13
DEQ	98	12	9	6	22	-5.811	105.695	118.6	4.6	26	13.61
DEQ	99	3	4	23	29	-5.534	105.796	195	4.2	22	19.78

Krakatau - section K2 - events in the Wadati-Benioff zone

type	yr	mon	day	hr	min	glat	glon	depth	mb	ntot	ser
DEQ	64	2	21	13	53	-6.722	105.485	34.3	5.1	14	28.34
DEQ	65	2	10	4	13	-6.043	105.949	147.7	5	28	17.84
DEQ	65	5	19	6	3	-6.601	105.389	64.8	5.6	60	13.44
DEQ	65	7	7	23	0	-6.956	105.531	75.5	5.4	101	8.75
DEQ	65	7	8	3	58	-6.922	105.491	65.4	5	52	10.64
LEQ	65	7	12	11	39	-7.091	105.444	51.6	0	18	15.44
DEQ	71	6	16	7	31	-6.981	105.297	83.6	5	37	17.16
DEQ	72	3	20	22	56	-6.859	105.384	55.4	5.3	41	18.9
DEQ	72	4	14	18	15	-6.744	105.616	56	5.2	41	14.54
LEQ	72	11	27	0	28	-8.022	104.857	145.6	0	13	20.21
DEQ	73	7	22	8	35	-6.673	105.549	56.7	5	75	15.2
DEQ	74	11	5	13	39	-6.923	105.304	83.9	5.1	42	20.08
DEQ	77	11	1	20	28	-5.942	105.851	105.7	5.3	96	10.7
DEQ	78	9	21	6	27	-6.803	105.445	63.4	5.4	102	12.98
DEQ	78	9	23	22	19	-6.763	105.545	63	4.7	39	16.76
LEQ	79	4	29	5	18	-7.903	104.978	45	4.7	29	12.37
FEQ	79	4	29	5	53	-7.869	104.952	35	4.6	40	9.86

DEQM	79	5	7	12	52	-6.379	105.92	118.9	5.9	267	4.18
XEQ	79	9	29	6	31	-6.43	105.717	71.5	4.6	14	46.14
DEQ	79	12	3	3	20	-6.868	105.306	69.1	5.1	64	8.29
DEQ	82	5	3	20	13	-5.982	105.845	114.9	5	52	10.38
DEQM	83	7	29	11	25	-6.693	105.521	53.2	5.3	229	5.18
LEQ	84	3	10	2	14	-6.713	105.529	91.4	4.9	68	8.64
DEQ	85	1	26	21	9	-6.109	105.877	143.5	5.1	98	9.36
DEQ	87	6	5	4	49	-6.146	105.856	122.7	5.1	57	11.43
LEQ	87	7	25	14	28	-8.071	104.553	26.6	4.7	26	14.23
LEQ	87	8	14	4	16	-6.593	105.626	92.1	4.7	16	22.75
DEQM	87	10	9	10	17	-7.891	105.199	33.5	5.1	210	5.72
LEQ	88	4	5	1	22	-6.631	105.476	51	4.8	27	18.65
LEQ	89	4	23	21	35	-6.625	105.717	96.1	4.9	86	9.25
DEQM	90	1	20	9	13	-6.615	105.894	85.1	5.2	181	6.78
DEQ	91	6	28	13	54	-6.688	105.429	76	5.2	136	6.62
DEQM	91	10	23	5	27	-7.019	105.315	55.2	5.2	93	13.38
DEQM	92	3	3	8	29	-5.939	106.08	139.4	5.1	120	8.8
DEQ	92	9	6	23	46	-7.068	105.423	27.7	5	79	10.72
DEQ	92	9	6	23	49	-7.064	105.485	36.8	4.9	55	13.02
DEQ	92	9	11	15	27	-7.171	105.412	28.5	4.4	25	12.04
DEQ	92	9	13	3	39	-6.679	105.737	96.8	5.1	75	9.92
DEQ	92	10	18	17	42	-6.774	105.551	62.9	5.7	322	4.96
DEQ	92	10	18	18	24	-6.811	105.556	56.4	4.7	24	25.42
DEQM	93	2	10	10	53	-7.766	105.187	44.4	5.5	232	5.48
LEQ	96	12	4	8	10	-6.782	105.577	151	4.4	26	15.03
DEQM	97	3	17	8	5	-6.716	105.334	28.1	5.8	362	4.99
FEQ	97	3	20	13	54	-7.056	105.436	35	4.5	50	14.31
FEQ	97	5	3	22	53	-6.772	105.291	35	4.6	63	8.58
DEQ	97	12	31	23	10	-6.335	105.972	138	4.1	39	16.28
DEQ	98	2	5	12	40	-8.539	104.81	35.8	4	19	25.95
LEQ	99	4	30	18	42	-6.732	105.533	35.6	4.4	13	27.93
LEQ	99	11	23	22	25	-6.789	105.452	59.7	4.1	19	14.76
FEQM	99	12	21	14	14	-6.849	105.53	42	6.2	392	3.76