Int J Earth Sci (Geol Rundsch) (2011) 100:1375–1381
DOI 10.1007/s00531-010-0543-0

ORIGINAL PAPER

Recent plumbing system of the Krakatau volcano revealed by teleseismic earthquake distribution

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Received: 8 January 2010 / Accepted: 21 March 2010 / Published online: 18 May 2010

Abstract Spatial and temporal analysis of global seismological data 1964–2005 reveals a distinct teleseismic earthquake activity producing a columnar-like formation in the continental wedge between the Krakatau volcano at the surface and the subducting slab of the Indo-Australian plate. These earthquakes occur continuously in time, are in the body-wave (m_b) magnitude range 4.5–5.3 and in the depth range 1–100 km. The Krakatau earthquake cluster is vertical and elongated in the azimuth N30°E, suggesting existence of a deep-rooted fault zone cutting the Sunda Strait in the SSW-NNE direction. Possible continuation of the fault zone in the SW direction was activated by an intensive 2002/2003 aftershock sequence, elongated in the azimuth of N55°E. Beneath the Krakatau earthquake cluster, an aseismic gap exists in the Wadati-Benioff zone of the subducting plate at the depths 100–120 km. We interpret this aseismic gap as a consequence of partial melting inhibiting stress concentration necessary to generate stronger earthquakes, whereas the numerous earthquakes observed in the overlying lithospheric wedge beneath the volcano probably reflect magma ascent in the recent plumbing system of the Krakatau volcano. Focal depth of the deepest events (~100 km) of the Krakatau cluster constrains the location of the primary magma generation to greater depths. The ascending magmatic fluids stress fault segments within the Sunda Strait fault zone and change their friction parameters inducing the observed tectonic earthquakes beneath Krakatau.

Keywords Subduction-related volcanoes · Krakatau · Earthquake distribution · Volcanic plumbing system

Electronic supplementary material The online version of this article (doi:10.1007/s00531-010-0543-0) contains supplementary material, which is available to authorized users.

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Introduction

The Krakatau volcano (6.1°S, 105.42°E), located in the Sunda Strait between Sumatra and Java, Indonesia, erupted catastrophically in 1883. After a quiescence of 44 years, the post-collapse cone of Anak Krakatau was constructed within the 1883 caldera. Anak Krakatau has been the site of frequent eruptions since 1927. Previous catastrophic eruptions of Krakatau are claimed to have occurred in 416 and 1680 (Simkin et al. 1981; Guschenko 1979; Stothers and Rampino 1983).

The international seismological centre (ISC) has provided monthly bulletins of reliable hypocentral determinations of teleseismic earthquakes since 1964, including events occurring in the Sunda Arc. Based on these commonly available data, we initially reported on the extraordinary concentration and specific distribution of teleseismic earthquakes beneath the Krakatau volcano in 2002 (Špičák et al. 2002). A concentrated occurrence of teleseismic earthquakes was later confirmed beneath several subduction-bound volcanoes (Špičák et al. 2004). Eruptions of Krakatau that occurred in October–November 2007 attracted attention of the public and media all over the world and prompted the Indonesian "Center of Volcanology and Geological Hazard Mitigation" (CVGHM) to raise the Alert Level on the volcano to 3 (on a scale of 1–4).

The position of the Sunda Strait in the regional tectonics is unique. The Sunda Strait marks the zone of transition

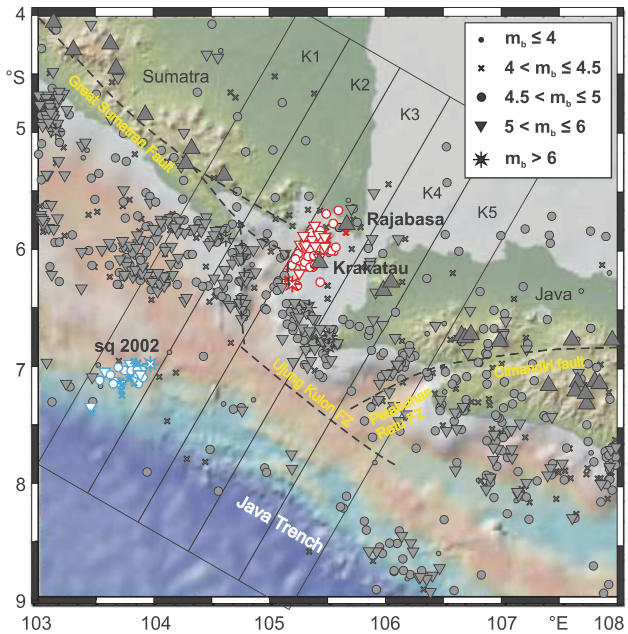

Fig. 1 Distribution of earthquake epicenters in the Sunda Strait region. For symbols of earthquakes with ISC magnitude see the *inset*. Epicenters of the Krakatau cluster are denoted by *red-outlined white symbols*, epicenters of the 2002/2003 aftershock sequence by *blue-outlined white symbols*, sections/swaths K1—K5 by rectangles, volcanoes by *larger grey triangles*

between an oblique subduction off Sumatra to a nearly orthogonal subduction off Java. Moreover, a distinct right (releasing) step in the trace of two prominent right-lateral strike-slip fault systems—the Great Sumatran fault in the NW and the Ujung Kulon fault zone in the SE—occurs in the Sunda Strait (Fig. 1). Most earthquakes in the Sunda Strait region belong to the Wadati-Benioff zone (WBZ) of the subducting Indo-Australian plate. Less distinct seismic activity in the overlying lithospheric wedge of the Eurasian plate can be attributed to several fault zones, including the two mentioned above (Hanuš et al. 1996; Malod and Kemal 1996; Schlüter et al. 2002). Špičák et al. (2002) delimited an anomalous concentration of earthquakes beneath Krakatau. The Krakatau volcano, situated in the middle of the Sunda Strait, belongs to the linear volcanic chain of the Sunda Arc. Rajabasa, another volcano of the Sunda Strait, is situated beyond the volcanic front some 50 km NNE of Krakatau.

Earthquake data and their analysis

For seismotectonic analysis of the Sunda Strait region, we use the EHB (after Engdahl, van der Hilst, and Buland) hypocentral determinations (International Seismological Centre, EHB Bulletin, http://www.isc.ac.uk, Internatl. Seis. Cent., Thatcham, United Kingdom, 2009) covering the period 1964–2005 and available global centroid moment tensor solutions (GCMTS) for the period 1976–2005. The EHB database, created using the algorithm of Engdahl et al. (1998), contains relocated events that are well-constrained teleseismically by arrival times reported to the ISC and to the National Earthquake Information Center (NEIC) for recent events. Three comments should be stressed: (1) though the EHB relocation filters out many events with low accuracy of hypocenter determination or with poor azimuthal coverage and most probably improves hypocentral determination of remaining well-recorded events, it does not give an image of an earthquake distribution that is significantly different from that given by ISC (NEIC) data; (2) the utilization of global seismological data has several advantages over other methods in the delineation of stressed bodies and their mutual relations in the complicated tectonic structure of convergent plate margins; and (3) a proper interpretation of earthquake foci distribution should constrain the assumptions used for geodynamic modeling.

To assist data users exploit the data set properly, the EHB database divides the hypocentral determinations to several classes according to their accuracy; recommendations for EHB data users can be found e.g., in Engdahl et al. (2007) and in the supplement to the EHB data set on request from E. R. Engdahl; a brief summary is given in Appendix 1.

The EHB data set comprises almost 900 events in the region of our interest (latitude 4–9°S, longitude 103–108°E—Fig. 1). Earthquake distribution in the Sunda Strait region is depicted by an epicentral map (Fig. 1) and vertical sections along swaths situated perpendicular to the convergent plate margin (Fig. 2). These figures enable us to discriminate between earthquakes belonging to the Wadati-Benioff zone of the subducting Indo-Australian plate and the two concentrated earthquake clusters—one representing a 2002/2003 aftershock sequence (see Sect. K1 in Figs. 1, 2) and the other spatially associated with the Krakatau volcano (see Sect. K3 in Figs. 1, 2; EHB data available in the Electronic Supplementary Material).

To determine the geometrical parameters—strike and dip—of the delimitated earthquake domains (the Wadati-Benioff zone, the 2002/2003 aftershock sequence, and the Krakatau cluster), we have approximated earthquake foci of the respective domain by a best-fitting plane using the least squares method. The procedure is described in detail in Špičák et al. (2007), a brief explanation is given in Appendix 2.

Results and interpretation

Parameters of the Wadati-Benioff zone in the Sunda Strait region determined by the approximation of spatial

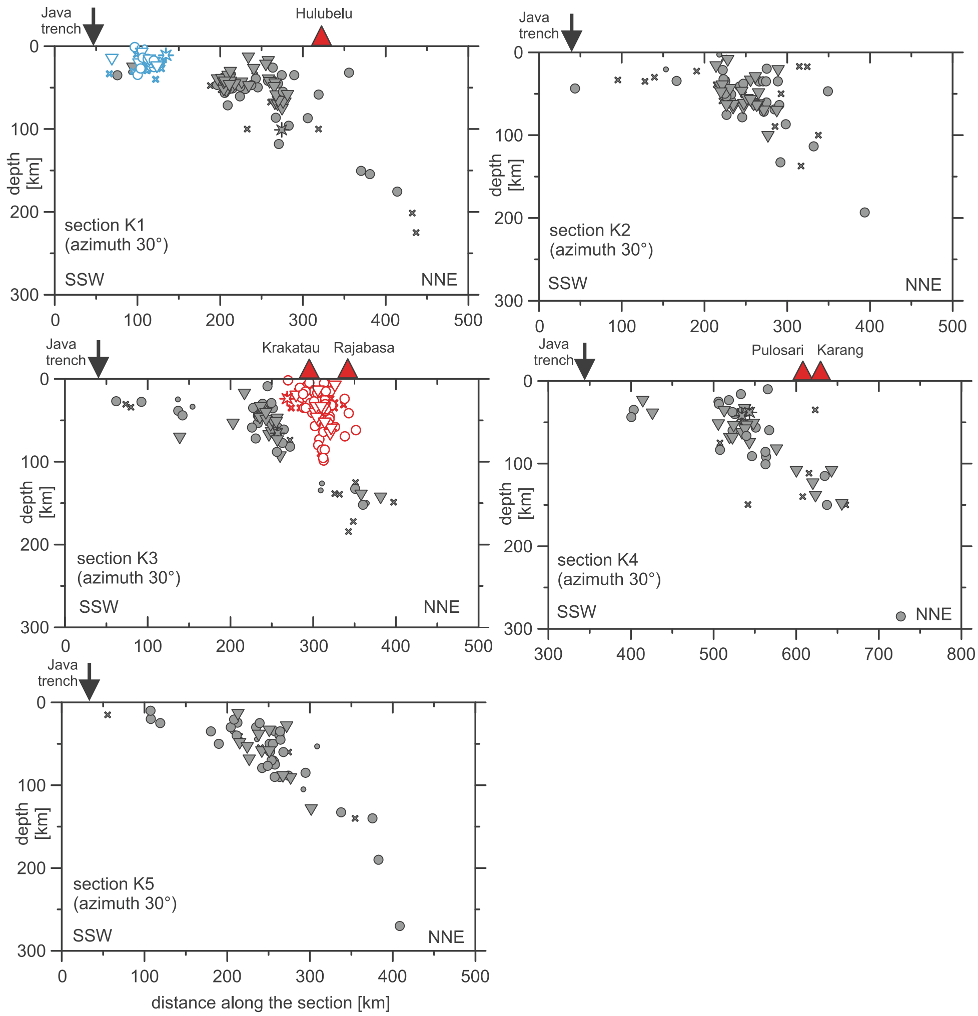

Fig. 2 Vertical sections along the swaths K1, K2, K3, K4, and K5 showing position of the Krakatau cluster (*red-outlined white symbols* in section K3) and of the earthquake foci of the 2002/2003 aftershock sequence (*blue-outlined symbols* in section K1) in comparison with sections without any distinct seismic activity outside the Wadati-Benioff zone (sections K2, K4, K5). Volcanoes denoted by red triangles, position of the Java trench by an arrow. See Fig. 1 for earthquake symbols and swath locations

distribution of the corresponding earthquake foci by the least squares method are strike 305° and dip 40° (for stability diagram see Fig. 3a).

The earthquake cluster 1964–2005 beneath the Krakatau volcano consists of 73 earthquakes. The EHB hypocentral data set is given in the Electronic Supplementary Material with its main characteristics summarized in Table 1. It should be stressed that the seismicity beneath Krakatau is quite energetic—more than 85% of the EHB events of the cluster are in the m_b magnitude range 4.5–5.3. The analysis forming the cluster as well as its relation to the regional seismicity and eruptive history of Krakatau enabled us to establish constraints on (1) its relation to regional tectonics, (2) the characteristics of the recent plumbing system of the volcano, and (3) a possible location of the source of primary magma. We expand on these three points below.

1. The Krakatau epicentral cluster (Fig. 4) is elongated in the SSW-NNE direction; the approximation of hypocenters resulted in a nearly vertical plane (dipping ~88°—see the stability diagram in Fig. 3b) and striking N30°E. We interpret this plane as a fault zone conjugate to the Great Sumatran and Ujung Kulon dextral strike-slip faults. The origin and function of the N30°E fault zone are probably related to the distinct bend of the convergent plate margin in the Sunda Strait area. In the same azimuth of 30°, the Rajabasa volcano occurs 50 km NNE of Krakatau, above the north–north-easternmost events of the earthquake cluster (Fig. 4). The strongest earthquake of the cluster, the January 15, 2002, m_b 6.3 event at the SSW edge of the cluster, was followed by the m_b 6.9 earthquake of June 27, 2002 (and its strong and numerous 2002/2003 aftershock sequence) in the lithospheric wedge behind the Java trench, well in front of the Wadati-Benioff zone (see earthquakes denoted by blue-outlined symbols in Figs. 1, 2). The 2002/2003 aftershock sequence consists of 31 EHB earthquakes; its main characteristics are given in Table 1. The plane approximating the distribution of events of the aftershock sequence is striking at 55°, in the direction to the Krakatau cluster. The equivocally determined dip of the plane (for the stability diagram of the approximation see Fig. 3c) as

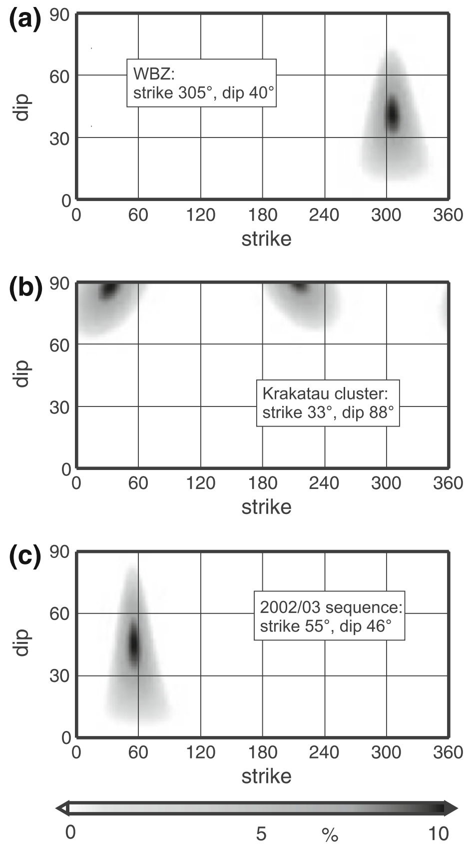

Fig. 3 Stability diagrams of optimum solutions of strike and dip of the plane approximating earthquake foci belonging to the Wadati-Benioff zone in the swaths K1—K5 in the Sunda Strait region (**a**), the Krakatau cluster of earthquakes (**b**), and the 2002/2003 aftershock sequence (**c**). The diagrams express the distribution of the best 10% of all solutions offered by the grid search of strike and dip. Values of optimum solutions of dip and strike are given

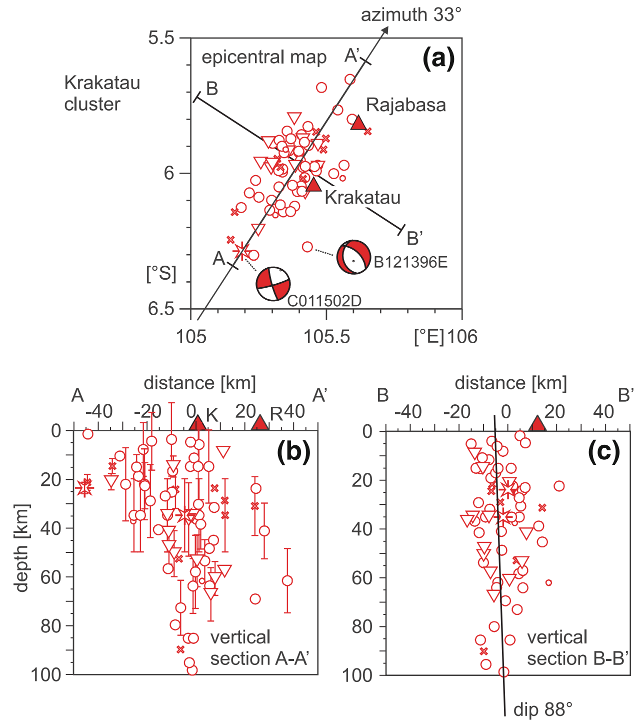

Fig. 4 The Krakatau cluster of earthquakes in a map view (**a**) and in vertical sections along (profile A–A′—(**b**)) and across (profile B–B′—(**c**)) the cluster. Standard errors in depth are denoted by *bars* for the DEQ and FEQ events (for FEQ events, they were fixed to 15 km). GCMTS fault plane solutions, map view. See Fig. 1 for earthquake symbols

well as variable focal mechanisms (Fig. 5) support the interpretation of the respective fault zone as a tectonic element with a complicated internal structure. The time succession of the two above-mentioned strong earthquakes and concurrence of planes approximating the Krakatau cluster and the 2002/2003 aftershock sequence suggest extensive, though not linear, fault zone breaking the lithospheric wedge of the Eurasian plate through the Sunda Strait at the length of about 300 km.

2. The spatial coincidence of the location and shape of the Krakatau epicentral cluster with the position of the Krakatau and Rajabasa volcanoes supports the interpretation that this focused earthquake occurrence is a consequence of recent dynamics of the plumbing system of these volcanoes rather than a consequence of non-magmatic plate boundary interactions. The continuous earthquake occurrence in time (Fig. 6) and the depth range of earthquake foci of the cluster (Table 1) point to a steady magma transport from depths greater than 75 km during the whole observation period. A comparison of the origin time of earthquakes of the cluster with the eruptive history of the Krakatau volcano (Fig. 6) does not show any correlation. The focal depths of earthquakes of the cluster, however, changed systematically with time, enabling us to delimitate seven time intervals according to variable focal depth of respective earthquakes (Fig. 7). The focal depths change from rather shallow (time interval I) through "intermediate-depth" (time interval II) to "deep" (time interval III); afterward, during time intervals IV–VII, the focal depths of earthquakes are systematically shallower. This time–depth interdependence resembles a cycle lasting approximately 40 ± 5 years. As mentioned above, the recent magma input seems to be reflected by infrequent earthquakes also beneath the Rajabasa volcano. If so, the plumbing system of the Rajabasa volcano is alive, though the last eruption of the volcano is unknown and its last increased activity was reported in April 1863 and May 1892 (Venzke et al. 2002). In the area of the Krakatau cluster, Harjono et al. (1991) observed the evolution of compression to extension with depth from mechanisms of shallow local events (focal depth

Table 1 Main characteristics of earthquakes of the Krakatau cluster and of the 2002/2003 aftershock sequence

Data set	Number of events	Main shock	m_b range	ISC depth range	EHB depth range	DEQ depth range	Number of						
							DEQ	BEQ	FEQ	LEQ	XEQ	Z	GCMTS
Krakatau	73	No main shock	3.3–6.3	0–108.9	1.7–98.5	4.6–72.9	24	0	14	34	1	0	2
Sq 2002/03	31	June 27, 2002, 05:50	3.3–6.9	10–34.7	9–34.6	9–34.6	25	3	0	3	0	0	8

For explanation of abbreviations see Appendix 1

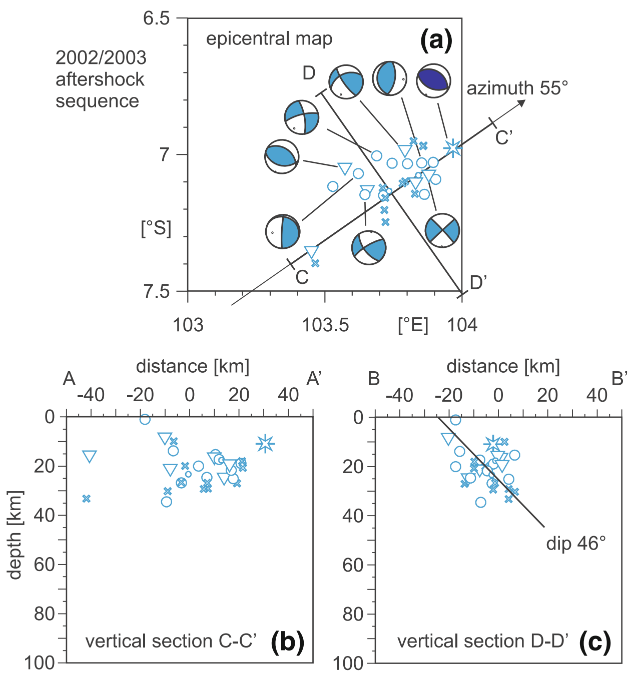

Fig. 5 The 2002/2003 aftershock sequence in a map view (**a**) and in vertical sections along (profile C–C′—(**b**)) and across (profile D–D′—(**c**)) the sequence. GCMTS fault plane solutions, map view; main shock heightened by *dark blue*. See Fig. 1 for earthquake symbols

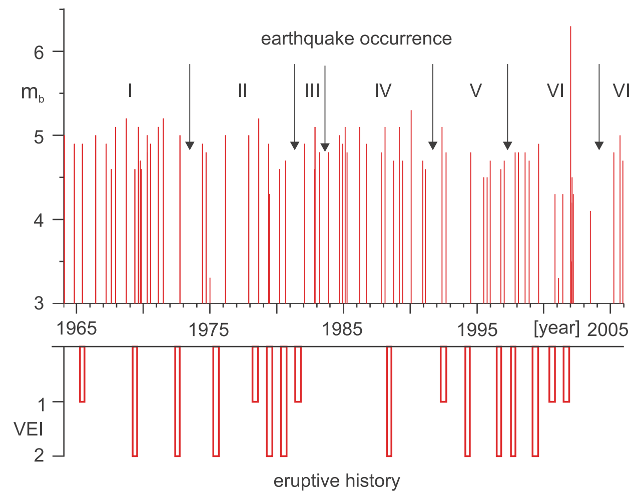

Fig. 6 Occurrence of earthquakes of the Krakatau cluster in time compared to eruptive history of the volcano between 1964 and 2005. Individual time intervals of seismic activity I–VII are limited by *arrows*. *VEI* volcano explosivity index, providing a relative measure of the explosiveness of volcanic eruptions, with maximum value 8, see e.g. http://en.wikipedia.org/wiki/Volcanic_Explosivity_Index

<20 km) obtained by a temporary (summer 1984) local network. The extension at the depth over 20 km seems to be supported by the B121396E normal mechanism (Fig. 4) and corresponds to the mechanisms observed beneath volcanoes at other convergent plate margins (Špičák et al. 2009).

3. The Krakatau volcano and the cluster of earthquakes beneath it are most probably related also to the intermediate-depth aseismic gap that is clearly detectable in the Wadati-Benioff zone at depths of 100–120 km beneath volcanoes (see Fig. 2—sections K1, K3, K4). As follows from our earlier studies, the intermediate-depth aseismic gap is not a phenomenon related specifically to Krakatau volcano but rather a general feature accompanying the subduction-related volcanoes all over the world (e.g. Špičák et al. 2004). The contrast of the aseismic gap in the Wadati-Benioff zone of the subducting slab at depths of about 100 km and of the occurrence of strong, teleseismically recorded earthquakes in the lithospheric wedge of the overlying plate probably reflects the differences in material properties of these two neighboring environments. The aseismic gap in the subducting slab may reflect a partly melted zone where the primary magma or its components are generated, whereas the earthquake cluster in the overlying lithospheric wedge probably represents prestressed, fractured brittle material activated seismically by the magma ascent.

Conclusions

We have documented a distinct teleseismic earthquake concentration beneath the Krakatau (and Rajabasa) volcanoes in the Sunda Strait in the time period 1964–2005. We explain the spatial coincidence of the earthquake cluster with the position of Krakatau and Rajabasa volcanoes and geometrical characteristics of the cluster as a combination of recent dynamics of the plumbing system

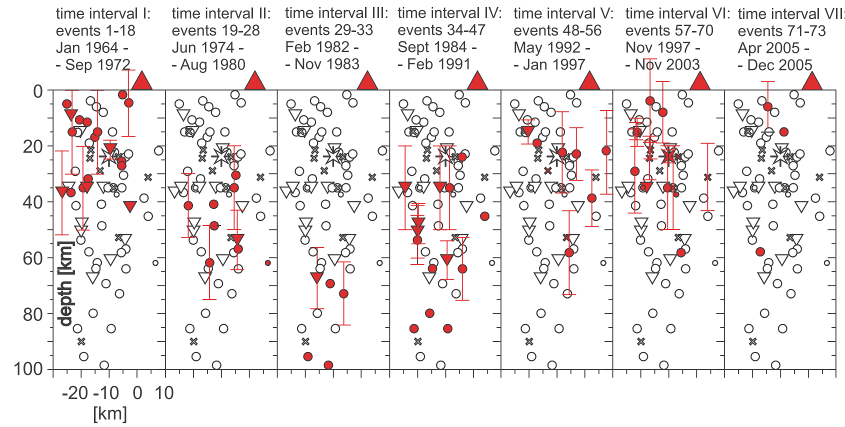

Fig. 7 Distribution of earthquake foci of the Krakatau cluster in vertical sections across the cluster (azimuth of sections 120°) in the time intervals I–VII. Earthquakes belonging to the appropriate time interval are heightened in *red* against the background of all earthquakes of the cluster (*open symbols*). Standard errors in depth are denoted by bars for the DEQ and FEQ events (for FEQ events, they were fixed to 15 km). Volcanoes Krakatau and Rajabasa (*in line*) denoted by *red triangles*. See Fig. 1 for earthquake symbols

of the volcanoes and the existence of an extensive fault zone stressed by the process of plate convergence. The continuous temporal occurrence of the earthquakes of the cluster (in contrast to episodic swarms and/or aftershock sequences) probably reflects a steady magma transport to the Earth surface. The magma ascent is spatially controlled by a N30°E striking fault zone that continues to the southwest in the slightly rotated azimuth of 50°, breaking the lithospheric wedge of the Eurasian plate in the Sunda Strait at the length of about 300 km. The position and geometrical parameters of the fault zone are revealed by a distribution of earthquake foci elongated in a N30°E direction for both the Krakatau cluster and the 2002/2003 aftershock sequence. Faults activated during the 2002/2003 aftershock sequence produced either left-lateral strike-slip or thrust faulting (Fig. 5). As the ascending magmatic fluids stress individual fault segments in the fault zone and act to reduce effective friction, earthquakes are induced along the Krakatau cluster within the fault zone. Focal depths of the deepest events of the cluster (at least 75 km or even more) constrain the location of the primary magma generation to greater depths. There an aseismic gap in the Wadati-Benioff zone of the subducting lithosphere occurs, indicating a possible partial melting of the subducting slab as a potential site of the primary magma generation. The gradual systematic change of focal depth of earthquakes of the Krakatau cluster from shallow to deep and then back to shallow in a cycle lasting 40 ± 5 years probably reflects depth variations of tectonic stress concentration rather than vertical migration of the source of magma. The observed time–depth pattern of teleseismic earthquake occurrence beneath Krakatau is unique among the subduction-related volcanoes as compiled by Špičák et al. (2009).

Acknowledgments This research was supported by Ministry of Education, Youth and Sports grant No. ME09011 (KONTAKT program). Map in Fig. 1 was prepared using GeoMapApp software, an integrated mapping application developed at Lamont-Doherty Earth Observatory. Our colleague M. Běhounková kindly performed approximation of earthquake foci of delimitated domains and prepared the stability diagrams of optimum solutions. We thank Dave Hill and Klaus Klinge for a careful review and valuable suggestions.

Appendix 1: EHB data

The arrival-time data for the EHB relocation have been extracted from ISC (International Seismological Centre) Bulletins for the 1964–2002 period and from the USGS EDR/PDE (Earthquake Data Report, Preliminary Determination of Epicenters) for the 2003–2005 period. The selected hypocenters have at least 15 teleseismic ($\Delta > 28°$) P arrivals used in the relocation. The catalogue is complete to M 5.5 but includes many events of smaller magnitude. As the accuracy of hypocenter determinations is crucial issue of each seismotectonic study, the authors of the EHB database categorized the events to several classes according to accuracy of the solution. Each class is characterized by a three-letter tag. The highest accuracy is represented by DEQ events (the most common tag) and FEQ events (depth of the event fixed to a standard depth; error in depth does not exceed 15 km). The events belonging to these classes are recommended for construction of vertical sections. BEQ events (depth fixed at depth determined from broadband observations) are not common; they are considered to be of high accuracy, too. LEQ events are poorly located in depth (standard error in depth >15 km), but they are recommended for epicentral maps. Use of XEQ events is not recommended at all. Letter Z is added in front of the tag when teleseismic azimuth gap of observations is greater than 180°; events marked by Z should be also omitted. Letter M is added behind the tag when GCMTS is available. For complete EHB hypocentral data for the Krakatau cluster and the 2002/2003 aftershock sequence see the Electronic Supplementary Material.

Appendix 2: approximation of a plane through earthquake foci

To determine strike and dip of delimited earthquake domains, we approximated a plane through earthquake hypocenters of the respective domain by the least squares method. An optimum approximating plane was found by grid search with 0.5° step in both strike and dip. The input hypocentral parameters can be weighted according to their accuracy expressed by the EHB tags (see Appendix 1). Our hitherto experience shows that the results of the approximation differ by only several degrees in both strike and dip for the whole hypocentral data set compared to the data set reduced peculiarly/exclusively to DEQ events (Špičák et al. 2007). The degree of unequivocalness of the optimum solution of strike and dip of the approximating plane can be qualified by a stability diagram that compares the optimum solution with the best 10% of all solutions (Fig. 3a, b, c).

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