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EARTHQUAKE DOUBLETS AND MULTIPLETS IN THE FIJI-TONGA-KERMADEC REGION

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Abstract

We investigated all the pairs of shallow, intermediate and deep earthquakes in the Harvard CMT catalogue that occurred between 1977 and July 2003 at a centroid distance of less than 40, 60 or 90 km and within a time interval of 200, 300 or 450 days for small, medium and large events, respectively. For the Fiji-Tonga-Kermadec area the Harvard catalogue lists 1022 shallow, 410 intermediate and 633 deep earthquakes of moment magnitude from 4.9 to 8.0. The magnitude threshold, above which the catalogue is complete, is 5.3-5.4, and the number of earthquakes of magnitude above this value is 691 for shallow, 329 for intermediate and 476 for deep events, respectively. The proportion of earthquakes, however, associated with doublets and multiplets against the total number of earthquakes is approximately the same in both data sets and therefore all earthquake pairs were considered regardless of their magnitude. We found 208 pairs of shallow, 31 of intermediate and 92 of deep events with moment magnitude from 5.0 to 7.2.

To check whether these earthquakes in pairs are really coupled and not connected by chance, the possibility of their occurrence in an uncorrelated Poissonian catalogue was considered. It was assumed that in such a catalogue the inter-event time is exponentially distributed, the earthquake magnitude follows the Gutenberg –Richter relation, and the distribution of centroid distances between the events in pairs is controlled by its non-parametric kernel estimate. The probability of appearance of the observed proportion of doublets of shallow earthquakes in the Poissonian catalogue was found to be very low, 5.64×10^{-6}, confirming the non-random character of observed pairs. The low probability of occurrence in a semi-random catalogue, created by randomising centroid locations in the actual dataset, indicates also high importance of the distance criterion used for a doublet specification. The time interval criterion is significantly less important, although the double events that occur shortly one after another are the least probable events to be uncorrelated.

In general, shallow earthquakes tend to form the pairs at smaller distances and within shorter time intervals than deep earthquakes. Both the distance and the time intervals do not depend on magnitude of involved events. The largest number of pairs of deep earthquakes is observed at a depth of about 600 km, and only a few pairs are found at a depth of 350-400 km. The proportion of deep events associated with doublets and multiplets against the number of all events increases also with depth. From comparison of focal mechanism of earthquakes in pairs, measured by the 3D rotation angle, it follows that deep earthquakes forming pairs have more diverse focal mechanism than shallow events. The rotation angle for three quarters of shallow earthquake pairs and only for about one third of deep earthquake pairs is smaller than 30 degrees.

Key words: Fiji-Tonga-Kermadec seismic region, earthquake multiplets, random catalogue, clustering test, focal mechanism, 3D rotation angle, fault rupture overlap.

1. INTRODUCTION

Earthquake interaction is a fundamental feature of seismicity, leading to earthquake sequences and clustering. An earthquake alters the shear and normal stress on surrounding faults. Such small, sudden stress changes may cause large changes in seismicity rate. The observed seismicity rate may be influenced by both static and dynamic effects (Stein, 1999). The new theoretical framework is based on calculation of the stress changes caused by one event and assessment where and what mechanism these changes may cause. To study such stress interaction, the computation of the stress field outside a rupturing fault is performed (e.g., King and Cocco, 2001). An interaction criterion that promises a better understanding of earthquake occurrence is Coulomb stress transfer (Stein, 1999). Modelling results demonstrate that transient loads, such as stress changes associated with passing seismic waves, advance the time of earthquakes that would have happened eventually as a result of constant background loading and that the triggering may be delayed (Gomberg *et al.*, 1997). Simple heuristic models and numerical calculations suggest, on the other hand, that an entire class of commonly invoked models of earthquake failure processes cannot explain triggering of seismicity by transient stress changes (Gomberg, 2001).

Global statistics of earthquake pairs reveal strong clustering in space and time, in which the occurrence of one earthquake increases the probability of a second earthquake, with the probability decaying with time and distance from the first event (Kagan and Jackson, 1991). There is no clear definition of an earthquake doublet or multiplet. Usually a doublet is defined, somewhat arbitrarily, as a pair of events with a magnitude difference of no more than 0.2 units, spatial separation smaller than 100 km, and temporal separation of a few years (Lay and Kanamori, 1980; Astiz and Kanamori, 1984), depending on how large the considered events are. Kagan and Jackson (1999) specified doublets as pairs of large earthquakes with centroids (centre of the deformation release) closer than their rupture size and occurring within a time interval shorter than the recurrence time inferred from plate motion.

Several studies show that earthquake doublets and multiplets occur in various parts of the Earth (e. g., Nomanbhoy and Ruff, 1996; Kagan and Jackson, 1999). The most often studied area are the Solomon Islands (Lay and Kanamori, 1980; Wesnousky *et al.*, 1986; Schwartz *et al.*, 1989; Xu and Schwartz, 1993), where one of the largest doublet rates in the world is observed (Felzer *et al.*, 2004). Earthquake doublets occur in Japan (Ando, 1975; Horikawa, 2001; Woessner *et al.*, 2004), in Mexico (Ortiz *et al.*, 2001; Yamamoto *et al.*, 2002; Quintanar *et al.*, 2004), and in California (Hudnut *et al.*, 1989).

The mechanism of triggering of earthquake doublets or multiplets is not well understood, but the generation of compound earthquakes indicates heterogeneity in the faulting process. In the Solomon Islands and New Britain subduction zones in particular, the largest earthquakes commonly occur as pairs with small separation in time and space (Lay and Kanamori, 1980; Schwartz *et al.*, 1989; Xu and Schwartz, 1993). This behaviour has been attributed to a specific pattern of fault plane heterogeneity consisting of closely spaced asperities (areas with increased strength) on the fault contact plane such that the failure of one asperity triggers slip in immediately adjacent asperities (Lay and Kanamori, 1980). The asperity distributions and a simple model of their interaction have been used to explain various features of large earthquakes in several subduction zones (Ruff, 1992). The subduction zone along the Middle America Trench shows many features similar to those in the Solomon Islands region. The relatively uniform asperity size there may be favourable for the occurrence of doublets (Astiz and Kanamori, 1984).

An alternative explanation for earthquake doublet generation in the Ometepec, Guerrero area in southern Mexico has been given by Yamamoto *et al.* (2002). They proposed that an observed discontinuity in the spatial distribution of aftershocks of the 1982 Ometepec doublet may reflect a segmentation of the continental margin crust and the upper part of the descending oceanic plate that may be casually related to the frequent earthquake doublet occurrence in the area.

Recently Felzer *et al.* (2004) demonstrated that the statistics of earthquake data in several catalogues are consistent with a single triggering mechanism responsible for the occurrence of aftershocks, foreshocks, and multiplets; and that they are caused by the same physical process. They find that the Solomon Islands multiplets may be explained simply by a high regional aftershock rate and earthquake density.

Two large ruptures, 11.4 hours apart, occurred on intersecting, nearly orthogonal, vertical faults during the 1987 Superstition Hills earthquake sequence in California

(Hudnut *et al.*, 1989). The first event ruptured a cross-fault and the second event initiated its rupture at the intersection of the cross-fault and the main fault and propagated along the main fault. To explain cross-fault triggering of a rupture on the main fault two hypotheses were used: slip on the cross-fault decreased locally normal stress on the main fault, and triggered the main fault rupture after a delay; and the delay was caused by fluid diffusion (Hudnut *et al.*, 1989).

The behaviour of the 1997 earthquake doublet in Kagoshima, Japan, was even more complex (Horikawa, 2001). The rupture of the first event was simple and well described by a single asperity. But the second event is characterized by successive rupture of multiple asperities on a conjugate fault system. Both the hypocenter and the largest asperity of the second event are located in a stress shadow caused by the first earthquake. Thus, a static stress change cannot explain rupture nucleation and spreading during the second event. Similarly, fluid migration and dynamic Coulomb failure stresses cannot explain its triggering, either. The coupled effect of static change in shear stress and normal stress under the rate- and state-dependent friction law was proposed as a possible mechanism of triggering (Horikawa, 2001).

The Fiji-Tonga-Kermadec region is one of the most interesting areas in the world, containing the most intense deep seismicity (e.g., Vavryčuk, 2004), caused by the subduction of the Pacific Plate under the Australian Plate with the rate of 10.5 cm/yr (e.g., DeMets *et al.*, 1990). The geometry of the slab is complex, especially in the north, where a sharp bending of the slab is observed (e.g., Giardini, 1992; Northard *et al.*, 1996). Variation in the slab dip with depth has also been reported (e.g., Northard *et al.*, 1996; Karato *et al.*, 2001). The inversion for anisotropy based on moment tensors of deep earthquakes indicates that the Tonga subduction zone is anisotropic with orthorhombic symmetry (Vavryčuk, 2004). The symmetry axes of anisotropy coincide with the principal stress directions in the slab.

The Fiji-Tonga-Kermadec region, displaying intense shallow and deep-focus seismicity, was selected for investigation of doublets and multiplets of shallow, intermediate and deep earthquakes. The selected area extends from 14°S to 33°S of latitude and from 177°E to 171°W of longitude.

2. DATA

The search for earthquake doublets and multiplets in the Fiji-Tonga-Kermadec region is based entirely on the Harvard CMT (centroid-moment tensor solutions) catalogue (Dziewonski *et al.*, 1981; Dziewonski and Woodhouse, 1983; Smith and Ekström, 1997; Ekström *et al.*, 2003) for the period from 1 January 1977 to 31 July 2003. The total number of earthquakes in the catalogue, after the removal by inspection of foreshocks and aftershocks, is 2065 in the moment magnitude M_w (Hanks and Kanamori, 1979) range between 4.9 and 8.0, as calculated from the seismic moment values M_0 listed in the catalogue. The earthquakes were divided into shallow events with depth

$h \leq 50$ km, intermediate events with $50 < h < 300$ km, and deep events with $h \geq 300$ km; their number is listed in Table 1. Their horizontal location in centroid coordinates (provided in the Harvard catalogue) is shown in Fig. 1, created using the GMT software (Wessel and Smith, 1995). Their vertical distribution is presented in Fig. 2.

Table 1

Number of all earthquakes and earthquake doublets and multiplets in the Fiji-Tonga-Kermadec region from 1 January 1977 to 31 July 2003 in the Harvard CMT catalogue

Item	Shallow $h \leq 50$ km	Intermediate $50 < h < 300$ km	Deep $h \geq 300$ km
All events Magnitude range	1022 4.9-7.5	410 4.9-8.0	633 5.0-7.7
All associated events Percentage of all events Magnitude range	372 36% 5.0-7.2	58 14% 5.2-6.8	169 27% 5.2-6.5
Earthquake pairs Percentage of all events	208 20%	31 8%	92 15%
Doublets Percentage of all pairs	127 61%	23 74%	62 67%
Pairs in triplets Percentage of all pairs	60 29%	8 26%	30 33%
Pairs in quadruplets Percentage of all pairs	21 10%		

The number of shallow and deep earthquakes with moment magnitude equal or greater than 5.4 is complete and follows the Gutenberg–Richter relation. The magnitude threshold for intermediate events is 5.3. The cumulative frequency–magnitude relations are shown in Fig. 3, where the corresponding values of the coefficient b are also given. The total number of such earthquakes is 1496; 72% of the total number in the catalogue. The number of shallow, intermediate, and deep events is given in Table 2.

The seismic moment tensor solutions, listed in the Harvard catalogue, were used to find similarities and differences between the focal mechanisms of two earthquakes forming a pair. For this, the 3D angle of rotation (Kagan, 1991) between two solutions, that would transform the focal mechanism of the first event into that of the second event, was calculated and taken into account for description of selected earthquakes.

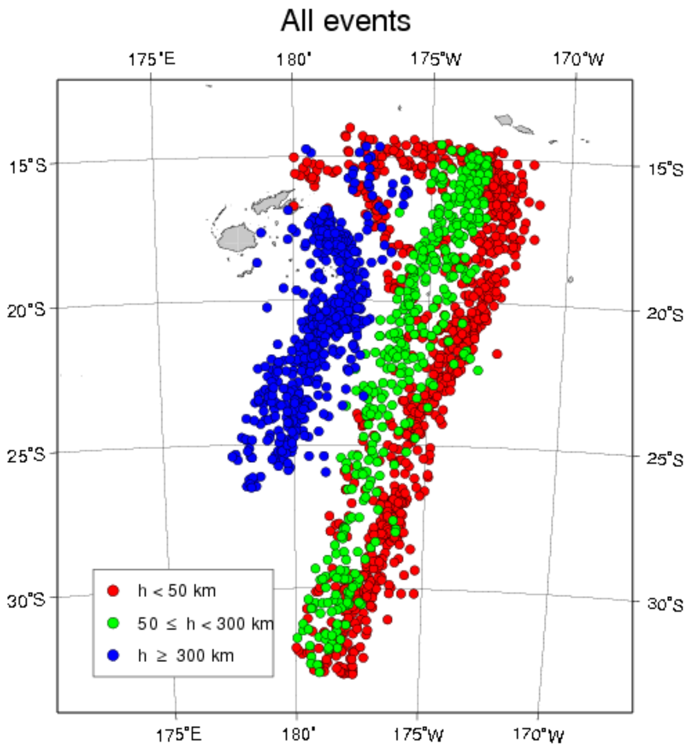

Fig. 1. Horizontal location in centroid coordinates of shallow (red circles), intermediate (green) and deep (blue) earthquakes in the Fiji-Tonga-Kermadec region from 1977 to July 2003.

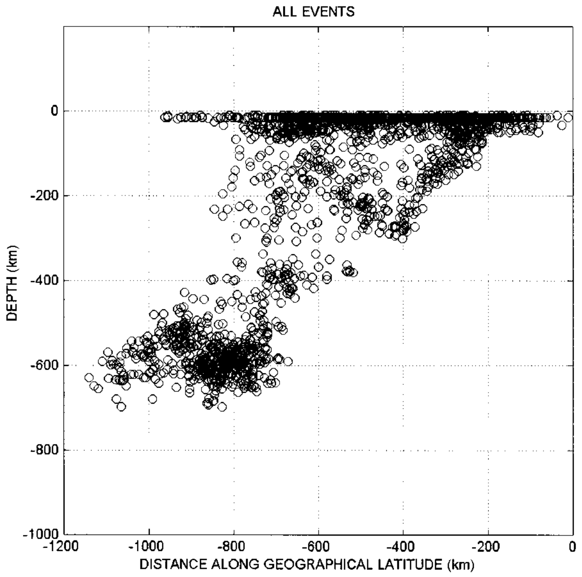

Fig. 2. Centroid depth distribution of earthquakes in the Fiji-Tonga -Kermadec region, shown as a cross-section along the geographical latitude, where 0 corresponds to the longitude of 171°W.

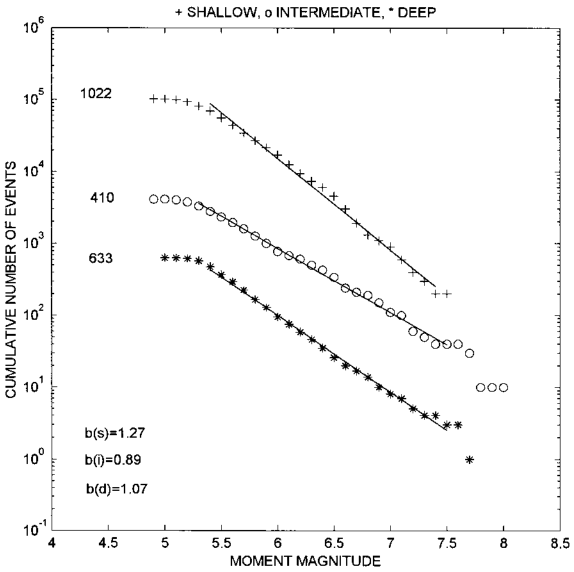

Fig. 3. Cumulative frequency –moment magnitude relations for shallow (crosses), intermediate (open circles) and deep (stars) earthquakes in the Fiji-Tonga -Kermadec region. For the sake of clarity, the curves for intermediate and shallow events are moved up by one and two decades, respectively. The total number of events is shown on the left-hand side of each curve. Their linear approximations are marked by straight lines, and the corresponding values of the slope coefficient *b* are also given.

Table 2

Number of earthquakes with magnitude equal or greater than 5.4 (5.3 for intermediate events) and earthquake doublets and multiplets in the Fiji-Tonga-Kermadec region from 1 January 1977 to 31 July 2003 in the Harvard CMT catalogue

Item	Shallow $h \leq 50$ km	Intermediate $50 < h < 300$ km	Deep $h \geq 300$ km
All events Magnitude range	691 5.4-7.5	329 5.3-8.0	476 5.4-7.7
All associated events Percentage of all events Magnitude range	284 41% 5.4-7.2	50 15% 5.3-6.8	142 30% 5.4-6.5
Earthquake pairs Percentage of all events	153 22%	30 9%	70 15%
Doublets Percentage of all pairs	96 63%	22 73%	49 70%
Pairs in triplets Percentage of all pairs	46 30%	8 27%	21 30%
Pairs in quadruplets Percentage of all pairs	11 7%		

3. SELECTION OF DOUBLETS AND MULTIPLETS

We specify a doublet as a pair of earthquakes with a magnitude difference of no more than 0.25 units, whose centroids are separated by no more than 40 km for events with magnitude from 5.0 to 5.4, 60 km for events with magnitude from 5.5 to 5.9, and 90 km for events with magnitude equal or greater than 6.0, and whose difference in time of occurrence is not longer than 200, 300 and 450 days, respectively. The shortest distance separation for the smallest earthquakes was chosen taking into account the accuracy of location of at least 10-15 km for a single event. The combined location errors in the ISC (International Seismological Centre) and CMT catalogues is about 25 km, even for large earthquakes, though the reliability of centroid locations is apparent (Smith and Ekström, 1997). For larger events the distance criterion was increased by a half, considering an increase of their rupture size. The selection of the time criterion is rather arbitrary, although it is distinctly shorter than that usually chosen, and is shorter than the recurrence time of earthquakes with given magnitudes.

In the first approach, all earthquake pairs fulfilling the described criteria were selected regardless of their magnitude. Two pairs would form a triplet and three pairs would form a quadruplet. Altogether, there are 331 pairs (16% of all events are the first events in a pair) out of 599 events associated with doublets and multiplets (29% of all events). The highest number of pairs is formed by shallow earthquakes and their lowest number comes from intermediate earthquakes (Table 1). Approximately two thirds of pairs are earthquake doublets and one third of them comes from triplets; there are a few quadruplets as well but formed by shallow earthquakes only. The horizontal location in centroid coordinates of all the earthquakes associated with doublets and multiplets is shown in Fig. 4, created using the GMT software (Wessel and Smith, 1995). Their vertical distribution is presented in Fig. 5. The number of shallow, intermediate and deep earthquakes associated with doublets and multiplets as a function of magnitude is shown in Fig. 6. The highest number of events is at the threshold magnitude of 5.3-5.4 and it decreases rapidly towards smaller magnitude values, where the number of events is incomplete.

The number of pairs of earthquakes with magnitude equal or greater than the threshold value is 253 (17% of all events are the first events in a pair), that is 76% of the total number of pairs. There are 476 events associated with doublets and multiplets, that is 32% of all events. Similarly as for all pairs, about two thirds of these pairs are earthquake doublets and one third of them comes from triplets. The corresponding statistics for shallow, intermediate, and deep earthquakes is given in Table 2.

Comparing statistics from Tables 1 and 2 it becomes apparent that the proportion of earthquakes associated with doublets and multiplets against the total number of earthquakes, and the proportion of pairs as well, is approximately the same in both the data sets, containing all events from the Harvard catalogue and those with magnitude equal and greater than its threshold value. We decided, therefore, to consider all earthquake pairs regardless of their magnitude. All the pairs of shallow events are listed in

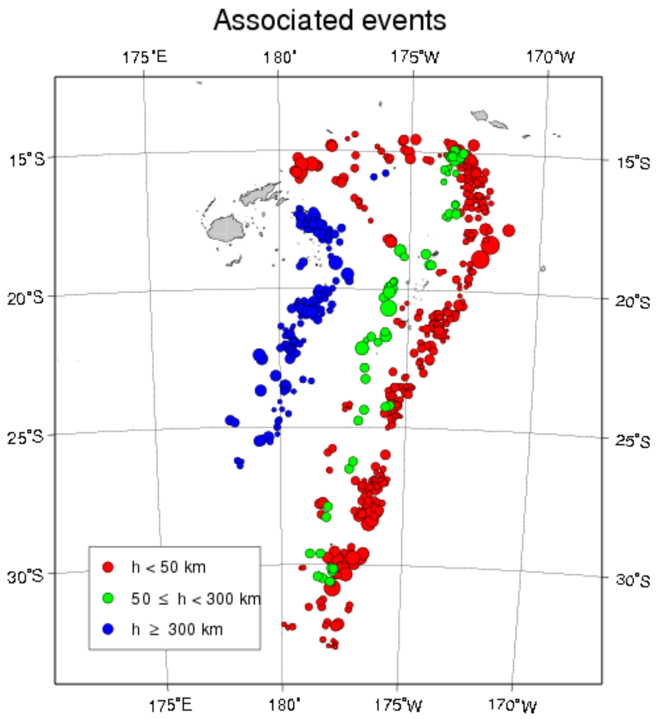

Fig. 4. Horizontal location in centroid coordinates of shallow (red circles), intermediate (green) and deep (blue) earthquakes associated with doublets and multiplets in the Fiji-Tonga-Kermadec region from 1977 to July 2003. The size of symbols is proportional to the earthquake magnitude.

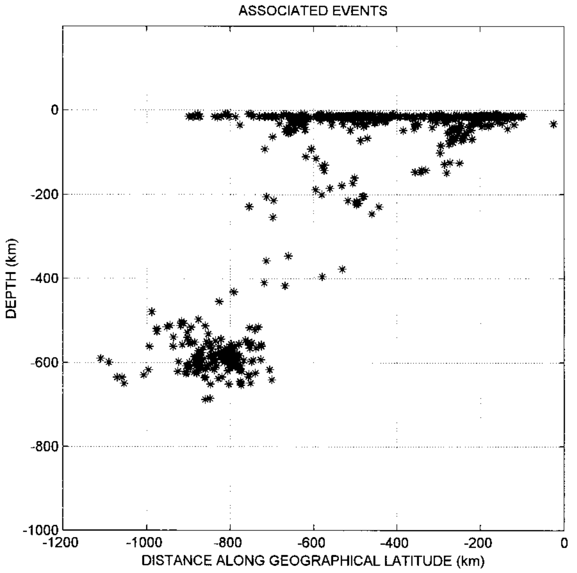

Fig. 5. Centroid depth distribution of earthquakes associated with doublets and multiplets in the Fiji-Tonga-Kermadec region, shown as a cross-section along the geographical latitude, where 0 corresponds to the longitude of 171°W.

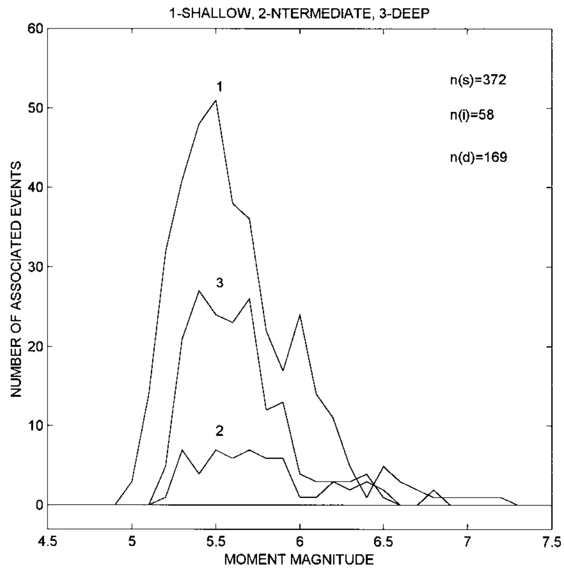

Fig. 6. The number of shallow (1), intermediate (2) and deep (3) earthquakes associated with doublets and multiplets as a function of moment magnitude. Their total numbers are also given.

Table 3, the pairs of intermediate events are listed in Table 4, and the pairs of deep events are given in Table 5. Some events forming multiplets are repeated when they appear in consecutive pairs.

4. TESTING OF NON-RANDOMNESS OF THE OCCURRENCE OF DOUBLETS

An essential question associated with the selected doublets is whether these pairs of earthquakes are really coupled or are connected by chance within the random structure of the catalogue. Although the answer cannot be provided for an individual pair, it is possible to determine the probability that the actual number of pairs could appear in an intrinsically uncorrelated set of events. If the clustering of doublets were mostly genuine, this probability would be low. We used this way of reasoning to test the non-randomness of the occurrence of shallow earthquakes forming the pairs. Limited number of deep doublets prevents the application of similar approach to deeper events.

In an uncorrelated Poissonian catalogue the inter-event time is exponentially distributed, and therefore the probability that an event satisfying certain criteria would occur within the time period τ after the preceding event is

$$\Pr\{T<\tau \mid criteria\} = 1-\exp\{-\lambda\tau\Pr[criteria]\}\,, \qquad (1)$$

where λ is the mean event rate and $\Pr[criteria]$ is the probability of fulfilling the criteria.

The applied criteria for the association of events in the earthquake catalogue are specified in the previous section. It is usually assumed that magnitude and source location are independent, and therefore for an event of magnitude m_0, the probability of fulfilling by chance the specified clustering criteria is

$$\Pr\left[criteria \mid m_0\right] = \left[F_m\left(m_0 + 0.25\right) - F_m\left(m_0 - 0.25\right)\right] G_r\left(m_0\right), \tag{2}$$

where $F_m(\cdot)$ is the magnitude cumulative distribution function,

$$G_r\left(m\right) = \begin{cases} F_r\left(40\ \mathrm{km}\right) & \text{for} \quad m \le 5.4 \\ F_r\left(60\ \mathrm{km}\right) & \text{for} \quad m \in \left[5.5,\ 5.9\right] \\ F_r\left(90\ \mathrm{km}\right) & \text{for} \quad m \ge 6.0 \end{cases} \tag{3}$$

and $F_r(\cdot)$ is the cumulative distribution function of centroid distance between two events.

In order to get $F_m(\cdot)$ function we accept the exponential distribution model (the Gutenberg–Richter model) for magnitudes exceeding the threshold value of catalogue completeness, which was found to be 5.4. Thus

$$F_m\left(m\right) = 1 - \exp\left[-\beta\left(m - 5.4\right)\right], \tag{4}$$

where $\beta = b \ln 10$ and b is the Gutenberg–Richter's constant whose maximum likelihood estimate from the studied shallow events is 1.20.

The fact that the magnitude distribution model (4) is applicable only for and above magnitude 5.4 limits our considerations to three quarters of selected doublets (Tables 1 and 2). This problem could be solved by a non-parametric representation of magnitude distribution – the approach similar to that presented below for the centroid distance distribution.

Unlike for magnitudes, we do not have any parametric model for centroid distances between earthquakes in the Fiji-Tonga-Kermadec region. Isacks *et al.* (1967) assumed that uncorrelated events are distributed randomly (i.e., follow a uniform distribution) in the space and time. Such an assumption for the spatial distribution is obviously incorrect because the particular geometry of fault system in an active region leads to specific patterns drawn by the hypocenters. A Poissonian earthquake process also accepts the preference of earthquake distribution following the spatial distribution of active faults. The non-uniform distribution of hypocenters (or centroids) leads in turn to a specific, usually complex distribution of hypocentral (or centroid) distances between the events, which is not known.

Although the parametric modelling of hypocentral distance distribution is not feasible, the distribution can be estimated by means of the non-parametric kernel density estimator (e.g., Silverman, 1986 and the references therein). From the previous experience in using this estimator for various earthquake problems (e.g., Lasocki *et al.*, 1997; Lasocki and Idziak, 1998; Lasocki and Kustowski, 2002; Orlecka-Sikora and Lasocki, 2005), we decided to use it here in the following form:

$$\hat{f}_r\left(r \mid \{r_i\},\{\alpha_i\},h\right)=\frac{1}{\sqrt{2\pi}N}\sum_{i=1}^{N}\frac{1}{\alpha_i h}\exp\left[-\frac{1}{2}\left(\frac{r-r_i}{\alpha_i h}\right)^2\right], \tag{5}$$

where $\{r_1, r_2, \ldots, r_N\}$ are the sample data, h is the smoothing factor which is a solution of the equation (Kijko *et al.*, 2001)

$$\sum_{i,j}\left\{2^{-0.5}\left[\frac{\left(r_i-r_j\right)^2}{2h^2}-1\right]\exp\left[-\frac{\left(r_i-r_j\right)^2}{4h^2}\right]-2\left[\frac{\left(r_i-r_j\right)^2}{h^2}-1\right]\exp\left[-\frac{\left(r_i-r_j\right)^2}{2h^2}\right]\right\}-2N=0 \tag{6}$$

and $\{\alpha_1, \alpha_2, \ldots, \alpha_N\}$ are the local bandwidth factors which force the estimator to be more appropriate for complex probability densities. The bandwidth factors are evaluated from the relation

$$\alpha_i=\left[\frac{\tilde{f}_r\left(r_i\right)}{g}\right]^{-0.5}, \tag{7}$$

where $\tilde{f}_r(\cdot)$ is the so-called “pilot estimate”, that is estimate (5) in which all α-s are set to 1.0 and $g=\left[\prod_{i=1}^{N}\tilde{f}_r\left(r_i\right)\right]^{\frac{1}{N}}$.

The distance between centroids is defined over $\mathbf{R}^+$, hence the estimator (5), which is applicable for a random variable defined over $\mathbf{R}^1$, must be modified (Silverman, 1986). The final density estimator for the centroid distance between the earthquakes is

$$\hat{f}_r^*\left(r \mid \{r_i\},\{\alpha_i\},h\right)=\frac{1}{\sqrt{2\pi}N}\sum_{i=1}^{N}\frac{1}{\alpha_i h}\left\{\exp\left[-\frac{1}{2}\left(\frac{r-r_i}{\alpha_i h}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{r+r_i}{\alpha_i h}\right)^2\right]\right\}, \quad r\ge 0 \tag{8}$$

and the cumulative distribution estimator for the epicentral distance is

$$\hat{F}_r^*\left(r \mid \{r_i\},\{\alpha_i\},h\right)=\frac{1}{N}\sum_{i=1}^{N}\left[\Phi\left(\frac{r-r_i}{\alpha_i h}\right)+\Phi\left(\frac{r+r_i}{\alpha_i h}\right)\right]-1.0, \quad r\ge 0, \tag{9}$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution.

Having 691 shallow earthquakes in the complete part of the catalogue (Table 2) one can build a sample of 691×690/2 = 238,395 distances between the centroids, which is far too large for the kernel estimation of density (8). From this huge sample we selected therefore, by random lot without replacement, a number of $N = 1000$ element sub-samples. For every sub-sample we estimated the kernel distribution functions (8), (9) and we accepted the respective averages of the results as the distribution functions representing the distribution of centroid distance. The final estimates are shown in Figs. 7 and 8. For particular critical distances, namely 40 km, 60 km and 90 km, we obtained $\hat{F}_r^*(40\,\mathrm{km}) = 0.0171$, $\hat{F}_r^*(60\,\mathrm{km}) = 0.0271$ and $\hat{F}_r^*(90\,\mathrm{km}) = 0.0446$.

The time filters determining doublets were $T < 200$ days for $m_0 < 5.5$, $T < 300$ days for $m_0 \in [5.5, 5.9]$, and $T < 450$ days for $m_0 \geq 6.0$, where m_0 is magnitude of the first event in the pair. The mean activity rate within the complete part of the catalogue of shallow earthquakes was $\lambda = 0.0712$ day^{-1}. When for any event of magnitude m_i from the complete part of the catalogue, we apply one of these time filters to relation (1), combined with relations (2)–(4) and (9), we obtain the probability p_i that in the

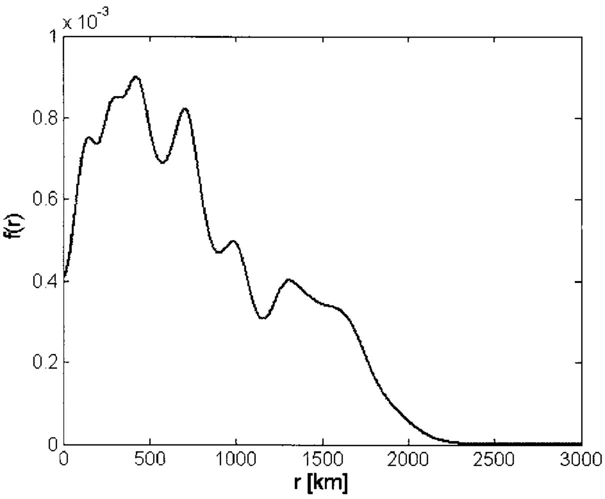

Fig. 7. The estimated probability density function of the distances between shallow earthquakes from the complete part of the catalogue.

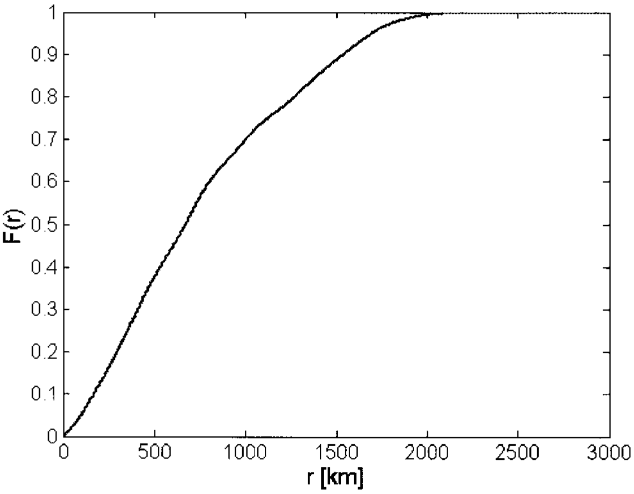

Fig. 8. The estimated cumulative distribution function of the distances between shallow earthquakes from the complete part of the catalogue.

uncorrelated catalogue an event satisfying the clustering criteria will follow the event m_i. There are 691 shallow earthquakes of magnitudes over the threshold of completeness. Therefore, the expected value of the number of doublets $\langle ND \rangle$, and the expected proportion of doublets P, provided that the catalogue is uncorrelated (Poissonian), are respectively

$$\langle ND \rangle = \sum_{i=1}^{690} p_i \ , \quad P = \frac{\langle ND \rangle}{690} \, . \tag{10}$$

The summation extends only to 690 because the last event in the catalogue does not have a chance to be coupled with any following event.

In a Poissonian catalogue, the number of doublets S follows the binomial distribution and the probability that this number would be equal to the number s actually observed is

$$\Pr(S = s) = \frac{n!}{s!(n-s)!} P^s (1-P)^{n-s} \, , \tag{11}$$

where n is the sample size.

For the complete part of the catalogue of shallow earthquakes the probability (11) is 5.64×10^{-6}, which confirms the conclusion on actual clustering of our doublets.

To complement our study, the presented procedure was repeated several times assuming different time filters defining doublets, starting from $T = 1$ day to $T = 425$ days. The obtained probability (11) is presented in Fig. 9. For all the considered time filters this probability is insignificant, which shows that the definition of time filters is not very important for selection of clustered events. Nevertheless, this probability is extremely small for short T and gradually increases with increasing T. This last result

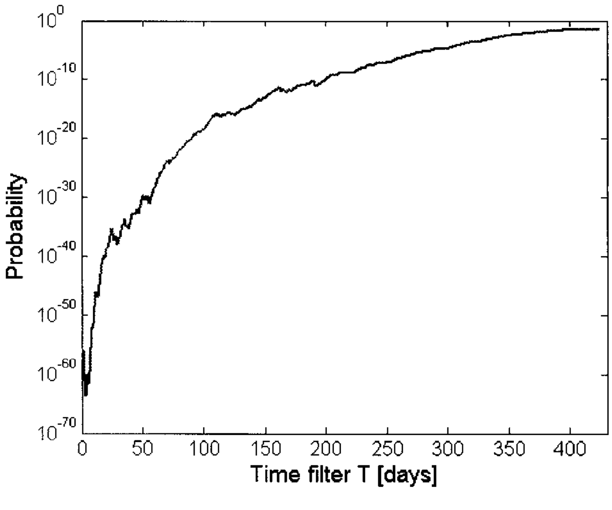

Fig. 9. The estimated probability of random occurrence of the observed number of doublets formed by shallow events separated by time intervals no longer than T as a function of the time filter length T.

indicates that the events that satisfy the magnitude and hypocentral distance criteria and occur shortly one after another are the least probable to be uncorrelated. Moreover, it can be also concluded that the time filters applied in this work were not the optimal ones.

In the next test, from the complete part of our original catalogue of shallow earthquakes from the Fiji-Tonga-Kermadec region we generated 1000 semi-random catalogues retaining the original sequences of magnitudes and times of occurrence and randomizing uniformly the sequence of hypocentral locations. The procedure is similar to that used by Nomanbhoy and Ruff (1996) who considered as random a catalogue in which the sequence of origin times was randomized. The prefix “semi” expresses our doubts whether the randomizing of hypocenter locations themselves is enough to convert a correlated catalogue into an uncorrelated one.

For every semi-random catalogue we found the number of associated pairs of events. Since the number of trials was large (1000), the average of the results and the sample standard deviation well estimated the expected value and standard deviation of the number of doublets in the uncorrelated population of 691 event series. The obtained average agreed within about 1.0 with the estimate of the expected number of doublets in the random catalogue, which indicates that the distance between the events has essential meaning for selection of doublets.

Assuming the normal distribution of the number of doublets in semi-random catalogues, one can readily estimate the probability that the actual number of doublets was just a random deviation from the evaluated average. This probability, i.e. the probability of obtaining the actual number of doublets, provided the catalogue was semi-random, was 2×10^{-6}. The result nicely corresponds to the probability estimated for the random catalogue (11) in the first test.

5. SHALLOW EARTHQUAKES

We have 208 pairs of shallow earthquakes whose centroids are located at a distance ranging from 1.5 to 92 km and whose time separation ranges from 0.013 to 421 days (Table 3). The distance against the time interval between two events forming a pair is shown on a logarithmic scale in Fig. 10. The distance increases slightly with increasing time interval. The distance of 25 km and time interval of 10 days are marked out to underline the pairs characterized by the shortest distance and shortest time interval. The distance of 25 km is directly related to the location accuracy of earthquakes. The interval of 10 days was selected from the distribution of time intervals as a function of time, clearly changing its shape after 10 days. There are 48 such distinct pairs, that is about a quarter of all pairs. There are, on the other hand, 89 pairs (43% of all pairs) with time intervals longer than 10 days and distances larger than 25 km.

The time interval and the distance between two events forming a pair appear to be not dependent on their average magnitude, although the pairs of larger earthquakes

Table 3

Pairs of shallow earthquakes ($h \leq$ 50 km) from the Harvard CMT catalogue. Δt is the time interval between two events, R is the distance, η is the degree of fault ruptures overlap, and Φ is the 3D rotation angle

No.	First event			Second event			Differences				Region
	date y m d	time h m	M_w	date y m d	time h m	M_w	Δt [day]	R [km]	η	Φ [deg]	
1	1977.03.23	07:19	6.3	1977.03.23	17:10	6.1	0.4	6.2	2.7	1	Fiji Is.
2	1977.10.26	02:20	5.7	1977.10.26	11:20	5.7	0.4	52	0.2	25	Fiji Is.
3	1977.12.04	05:50	6.2	1977.12.05	14:13	6.0	1.3	60	0.2	10	S of Fiji Is.
4	1977.12.05	14:13	6.0	1977.12.08	06:15	6.0	2.6	30	0.4	5	S of Fiji Is.
5	1978.01.14	15:20	6.3	1978.01.15	06:56	6.2	0.6	14	1.3	14	Kermadec Is.
6	1978.01.15	06:56	6.2	1978.02.10	19:32	6.2	26	44	0.4	7	Kermadec Is.
7	1978.03.17	11:00	5.6	1979.01.07	00:25	5.8	296	54	0.2	92	Tonga Is.
8	1978.08.17	08:51	6.0	1979.07.24	00:54	6.2	341	52	0.3	16	Tonga Is.
9	1978.10.31	16:54	5.8	1978.11.24	22:22	5.7	24	53	0.2	34	Kermadec Is.
10	1978.11.24	22:22	5.7	1979.01.07	10:51	5.7	44	7.8	1.1	29	Kermadec Is.
11	1979.07.24	00:54	6.2	1980.03.31	13:04	6.1	250	7.3	2.1	19	Tonga Is.
12	1979.03.19	00:02	5.5	1979.03.19	07:45	5.4	0.3	24	0.3	15	Tonga Is.
13	1979.11.28	14:54	5.5	1979.12.17	01:33	5.4	19	32	0.2	3	Kermadec Is.
14	1979.12.27	07:45	5.7	1980.01.21	02:38	5.5	26	20	0.4	85	Tonga Is.
15	1980.02.03	11:58	6.3	1980.12.15	08:12	6.3	315	90	0.2	68	Tonga Is.
16	1980.02.21	11:13	5.6	1980.02.21	14:24	5.8	0.1	7.7	1.2	10	Kermadec Is.
17	1980.03.27	15:29	5.9	1980.03.27	15:56	5.8	0.02	13	0.8	34	Tonga Is.
18	1980.07.02	15:48	5.5	1981.01.09	02:18	5.5	190	47	0.1	76	Tonga Is.
19	1980.11.24	10:00	5.4	1980.11.25	10:18	5.4	1.0	40	0.1	28	Tonga Is.
20	1981.01.09	02:18	5.5	1981.07.06	01:02	5.7	178	50	0.2	88	Tonga Is.
21	1981.03.11	07:17	5.6	1981.04.10	16:48	5.6	30	29	0.3	10	Tonga Is.
22	1981.05.08	17:04	5.0	1981.06.01	14:07	5.2	24	26	0.2	71	Tonga Is.
23	1981.12.24	05:33	6.9	1981.12.26	17:05	7.1	2.5	22	2.1	7	Kermadec Is.
24	1981.12.24	22:36	5.8	1981.12.25	09:12	5.6	0.4	1.5	5.7	16	Kermadec Is.
25	1982.08.07	00:31	5.2	1982.09.18	00:20	5.1	42	31	0.1	4	Tonga Is.
26	1982.08.07	18:20	5.9	1983.06.05	13:59	5.8	300	30	0.3	4	Samoa Is.
27	1982.09.11	06:31	5.3	1982.09.12	08:46	5.5	1.1	14	0.4	24	Kermadec Is.
28	1982.09.12	08:46	5.5	1982.09.14	12:42	5.3	2.2	46	0.1	31	Kermadec Is.
29	1982.09.18	00:20	5.1	1982.11.07	07:21	5.2	50	21	0.2	8	Tonga Is.
30	1982.09.18	21:20	5.8	1982.09.20	17:05	5.7	1.8	16	0.6	13	S of Fiji Is.
31	1982.09.20	17:05	5.7	1982.11.11	21:21	5.7	52	58	0.2	14	S of Fiji Is.
32	1982.11.22	05:32	5.4	1982.12.03	01:38	5.6	11	44	0.2	9	S of Fiji Is.
33	1982.11.27	02:19	5.6	1982.12.19	00:06	5.5	22	15	0.5	7	S of Kermadec Is.
34	1983.04.27	17:20	5.7	1983.04.30	02:51	5.6	2.4	43	0.2	10	Tonga Is.
35	1983.05.11	21:48	5.7	1983.12.04	19:30	5.5	207	45	0.2	63	Tonga Is.
36	1983.06.01	10:58	6.2	1984.04.21	12:36	6.0	324	28	0.5	86	Samoa Is.

37	1983.12.03	01:24	6.1	1984.03.23	20:31	6.0	112	35	0.4	27	Samoa Is.
38	1984.07.17	01:25	5.3	1984.11.12	13:08	5.5	118	27	0.2	66	Tonga Is.
39	1984.07.21	00:15	5.4	1984.09.04	20:44	5.4	46	19	0.3	43	Samoa Is.
40	1984.09.17	09:08	6.2	1984.09.22	21:44	6.1	5.5	13	1.3	3	S of Kermadec Is.
41	1984.10.06	02:52	5.8	1985.01.02	22:29	5.7	88	34	0.3	10	Samoa Is.
42	1984.10.12	02:03	6.0	1984.11.17	22:43	6.2	36	4.7	3.3	21	Tonga Is.
43	1984.10.22	15:26	5.5	1984.10.30	20:33	5.5	8.2	18	0.4	9	Kermadec Is.
44	1985.02.09	20:33	5.4	1985.02.16	13:48	5.4	6.7	39	0.1	13	Tonga Is.
45	1985.02.15	09:21	5.4	1985.02.16	13:48	5.4	1.2	28	0.2	20	Tonga Is.
46	1985.08.21	10:43	5.9	1986.06.11	06:18	6.0	293	86	0.1	32	Fiji Is.
47	1985.08.27	07:39	5.7	1985.12.31	14:04	5.8	126	46	0.2	98	Tonga Is.
48	1985.12.22	17:13	6.0	1985.12.22	18:27	6.0	0.05	4.4	2.9	5	Fiji Is.
49	1986.01.17	07:19	5.2	1986.05.25	12:25	5.3	128	37	0.1	11	S of Tonga Is.
50	1986.05.24	10:43	6.0	1986.07.01	00:49	6.1	38	65	0.2	27	Samoa Is.
51	1986.06.24	17:39	5.9	1986.06.24	19:31	6.0	0.08	44	0.3	19	Kermadec Is.
52	1986.06.24	19:31	6.0	1986.06.29	11:57	6.1	4.7	14	0.9	8	Kermadec Is.
53	1986.08.05	11:15	5.3	1986.08.05	19:17	5.2	0.4	19	0.3	54	S of Fiji Is.
54	1986.08.05	19:17	5.2	1986.08.12	00:59	5.4	6.2	13	0.4	67	S of Fiji Is.
55	1986.08.12	00:59	5.4	1986.08.24	10:45	5.3	12	19	0.3	30	S of Fiji Is.
56	1986.08.24	13:03	5.2	1986.10.22	22:20	5.4	59	33	0.1	17	Kermadec Is.
57	1986.10.20	14:41	6.0	1986.10.20	18:16	5.9	0.15	21	0.6	12	Kermadec Is.
58	1986.10.20	18:16	5.9	1986.11.07	19:49	6.1	18	43	0.3	9	Kermadec Is.
59	1986.10.20	19:39	5.8	1986.10.21	11:03	5.9	0.6	29	0.4	80	Kermadec Is.
60	1986.10.20	22:51	5.6	1986.11.08	04:22	5.5	18	21	0.3	12	Kermadec Is.
61	1986.10.21	06:50	5.7	1987.01.04	01:39	5.8	75	32	0.3	4	Kermadec Is.
62	1986.10.21	11:03	5.9	1986.10.21	12:29	5.9	0.06	37	0.3	80	Kermadec Is.
63	1986.10.22	19:40	5.5	1986.11.10	20:38	5.6	19	23	0.3	21	Kermadec Is.
64	1986.11.07	19:49	6.1	1986.12.20	08:21	6.0	43	14	1.1	7	Kermadec Is.
65	1986.11.08	04:22	5.5	1986.11.12	20:54	5.6	4.7	13	0.5	14	Kermadec Is.
66	1986.12.01	12:30	6.1	1986.12.01	12:53	6.0	0.02	25	0.5	10	Kermadec Is.
67	1986.12.12	03:18	5.2	1986.12.13	18:02	5.4	1.6	2.3	2.2	13	S of Fiji Is.
68	1987.03.07	19:43	5.7	1987.12.10	09:24	5.6	278	53	0.2	88	Samoa Is.
69	1987.03.26	06:47	5.6	1987.05.19	16:58	5.6	54	31	0.3	25	Tonga Is.
70	1987.08.14	08:24	5.4	1987.12.07	00:00	5.5	115	48	0.1	10	Samoa Is.
71	1987.10.06	04:19	7.3	1988.10.08	04:46	7.1	368	75	0.8	83	Tonga Is.
72	1987.12.07	00:00	5.5	1987.12.25	00:33	5.4	18	27	0.2	26	Samoa Is.
73	1987.12.25	00:33	5.4	1988.05.29	06:24	5.5	155	32	0.2	9	Samoa Is.
74	1988.01.13	22:16	5.3	1988.01.17	13:51	5.5	3.7	19	0.3	27	S of Kermadec Is.
75	1988.01.17	13:51	5.5	1988.01.18	09:53	5.3	0.8	34	0.2	9	S of Kermadec Is.
76	1988.03.23	05:07	5.3	1988.03.23	13:43	5.5	0.4	9.1	0.6	16	Kermadec Is.
77	1988.03.23	13:43	5.5	1989.01.13	03:42	5.3	296	37	0.2	26	Kermadec Is.
78	1988.04.02	14:26	6.3	1988.12.05	16:05	6.3	246	73	0.3	73	Tonga Is.
79	1988.07.01	02:07	5.7	1988.07.01	02:55	5.9	0.03	31	0.3	12	Fiji Is.

80	1988.07.01	02:55	5.9	1989.07.06	17:25	6.0	371	20	0.6	13	Fiji Is.
81	1988.08.22	13:54	5.1	1988.09.15	08:58	5.2	25	33	0.1	22	Samoa Is.
82	1988.12.08	11;18	5.6	1988.12.08	12:02	5.5	0.03	16	0.4	22	Tonga Is.
83	1989.02.25	11:26	6.7	1989.05.14	01:00	6.9	77	88	0.4	3	Kermadec Is.
84	1989.04.08	03:06	6.0	1989.05.28	09:46	5.8	50	30	0.4	108	Tonga Is.
85	1989.05.28	09:46	5.8	1990.01.20	07:20	5.8	237	42	0.2	86	Tonga Is.
86	1989.06.23	00:35	5.4	1989.07.08	00:48	5.3	15	12	0.4	37	Samoa Is.
87	1989.07.29	05:48	5.1	1989.08.09	00:40	5.2	11	28	0.2	30	Tonga Is.
88	1989.08.12	20:46	5.5	1990.01.22	02:32	5.4	162	37	0.2	39	Tonga Is.
89	1990.01.14	21:04	6.1	1990.01.18	12:45	6.0	3.6	36	0.4	2	Kermadec Is.
90	1990.01.16	07:36	5.7	1990.01.16	07:56	5.6	0.01	29	0.3	32	Kermadec Is.
91	1990.01.16	07:56	5.6	1990.01.16	10:52	5.6	0.1	48	0.2	34	Kermadec Is.
92	1990.01.16	10:52	5.6	1990.05.15	21:33	5.7	119	53	0.1	11	Kermadec Is.
93	1990.01.21	16:43	5.4	1990.01.22	02:32	5.4	0.4	32	0.2	32	Tonga Is.
94	1990.02.16	06:22	5.3	1990.04.04	05:40	5.3	47	33	0.2	40	Tonga Is.
95	1990.03.13	01:04	5.4	1990.03.24	17:20	5.4	12	25	0.2	53	Samoa Is.
96	1990.04.06	16:31	5.8	1990.04.09	09:31	6.0	2.7	62	0.2	38	S of Fiji Is.
97	1990.04.28	11:42	5.7	1990.08.27	04:12	5.7	121	24	0.3	31	S of Fiji Is.
98	1990.11.25	01:00	5.7	1990.11.25	03:36	5.8	0.1	15	0.6	8	Tonga Is.
99	1990.12.21	05:29	6.1	1991.01.01	17:28	6.0	11.5	88	0.2	8	Tonga Is.
100	1990.12.24	08:22	5.3	1991.02.01	12:07	5.4	39	15	0.3	27	Tonga Is.
101	1991.01.01	17:28	6.0	1991.08.05	06:05	6.0	215	45	0.3	8	Tonga Is.
102	1991.03.31	22:39	5.4	1991.04.01	01:59	5.5	0.1	7.5	0.8	8	Samoa Is.
103	1991.10.30	10:35	6.2	1992.12.24	00:34	6.2	422	61	0.3	16	Tonga Is.
104	1991.12.11	06:29	5.5	1992.07.18	15:31	5.7	220	59	0.1	7	Tonga Is.
105	1992.05.12	14:47	5.5	1992.05.13	18:26	5.6	1.1	28	0.2	10	S of Fiji Is.
106	1992.06.25	06:31	6.5	1993.06.18	11:52	6.6	359	52	0.5	18	Kermadec Is.
107	1992.07.18	15:31	5.7	1992.09.10	22:09	5.6	54	55	0.1	16	Tonga Is.
108	1992.09.10	10:43	6.0	1993.01.04	20:41	6.0	117	53	0.2	9	Tonga Is.
109	1992.09.24	20:18	5.5	1993.02.20	07:11	5.5	149	24	0.3	57	Tonga Is.
110	1992.10.22	09:04	6.5	1992.10.22	23:08	6.4	0.6	20	1.2	8	Kermadec Is.
111	1992.10.22	23:08	6.4	1992.10.24	08:23	6.6	1.4	43	0.6	7	Kermadec Is.
112	1993.03.11	22:07	5.7	1993.07.20	07:38	5.7	130	20	0.4	12	Samoa Is.
113	1993.04.08	00:19	5.2	1993.06.06	06:18	5.1	59	7.4	0.5	10	S of Tonga Is.
114	1993.05.04	00:09	5.6	1993.05.15	05:23	5.6	11	50	0.2	6	Kermadec Is.
115	1993.06.06	09:18	5.5	1993.06.10	17:48	5.6	4.3	20	0.4	9	S of Tonga Is.
116	1993.06.18	11:52	6.6	1993.06.18	17:57	6.5	0.25	19	1.4	4	Kermadec Is.
117	1993.11.24	11:27	5.4	1993.11.29	06:35	5.3	4.8	17	0.3	6	Tonga Is.
118	1993.12.13	11:43	5.8	1993.12.14	06:31	6.0	0.8	16	0.7	11	Tonga Is.
119	1994.01.15	17:03	5.7	1994.02.09	19:27	5.5	25	36	0.2	10	Tonga Is.
120	1994.01.16	10:18	5.4	1994.04.22	09:36	5.3	96	27	0.2	38	Tonga Is.
121	1994.04.01	19:48	5.5	1994.07.28	01:39	5.3	117	26	0.2	21	Samoa Is.
122	1994.04.04	01:37	5.8	1994.08.30	10:14	5.8	148	21	0.4	42	Tonga Is.

123	1994.06.18	02:21	5.4	1994.12.25	11:43	5.5	190	12	0.5	20	Kermadec Is.
124	1994.07.23	12:58	5.9	1995.05.07	22:38	6.0	288	62	0.2	6	Tonga Is.
125	1994.07.24	09:06	5.6	1994.10.31	23:04	5.5	100	15	0.4	19	Tonga Is.
126	1994.08.29	08:31	5.4	1994.08.29	09:31	5.4	0.04	18	0.3	7	Tonga Is.
127	1994.08.30	10:14	5.7	1994.09.12	22:43	5.9	14	60	0.2	20	Tonga Is.
128	1994.09.12	23:35	5.5	1994.09.14	11:45	5.5	1.5	44	0.1	81	Tonga Is.
129	1994.09.12	23:35	5.5	1995.04.08	17:12	5.5	207	37	0.2	59	Tonga Is.
130	1994.10.20	04:05	5.5	1995.03.31	16:40	5.7	162	60	0.1	76	Tonga Is.
131	1995.01.08	13:41	5.3	1995.01.26	05:16	5.5	18	56	0.1	19	S of Fiji Is.
132	1995.01.22	12:04	5.5	1995.01.24	17:57	5.6	2.2	14	0.5	7	S of Fiji Is.
133	1995.01.24	17:57	5.6	1995.01.25	19:00	5.7	1.1	21	0.4	13	Kermadec Is.
134	1995.03.03	21:12	5.9	1995.10.02	23:48	6.0	212	47	0.3	23	Samoa Is.
135	1995.04.11	21:33	5.3	1995.11.20	18:07	5.5	223	2.0	2.8	8	Kermadec Is.
136	1995.04.16	20:36	5.2	1995.04.30	11:50	5.2	15	24	0.2	29	Tonga Is.
137	1995.05.21	16:50	5.6	1995.05.23	07:20	5.5	1.6	16	0.5	7	Kermadec Is.
138	1995.05.28	05:57	5.6	1995.07.08	23:49	5.7	42	40	0.2	13	S of Fiji Is.
139	1995.07.08	23:49	5.7	1995.11.07	13:55	5.8	121	12	0.7	15	S of Fiji Is.
140	1995.08.02	21:39	5.4	1995.08.04	06:38	5.3	1.3	40	0.1	8	S of Kermadec Is.
141	1995.08.30	23:04	5.8	1995.09.25	01:10	5.7	25	51	0.2	11	Tonga Is.
142	1995.08.31	20:39	5.6	1995.09.29	04:09	5.5	28	24	0.3	16	Tonga Is.
143	1995.11.13	07:38	6.0	1996.02.16	11:34	5.9	95	27	0.5	2	Tonga Is.
144	1995.12.25	03:06	6.0	1995.12.25	03:24	5.8	0.01	41	0.3	13	Kermadec Is.
145	1996.03.04	17:13	5.5	1996.10.31	23:28	5.3	241	16	0.3	18	Tonga Is.
146	1996.06.28	02:41	5.6	1996.06.28	09:34	5.6	0.3	12	0.6	27	Tonga Is.
147	1996.10.30	22:57	5.7	1996.10.30	23:30	5.6	0.02	21	0.4	3	S of Fiji Is.
148	1996.11.15	10:40	5.5	1996.11.17	08:34	5.7	1.9	15	0.5	20	Fiji Is.
149	1997.03.30	08:38	5.7	1997.06.25	03:54	5.8	87	53	0.2	51	Tonga Is.
150	1997.05.03	10:42	5.4	1997.09.25	23:26	5.4	145	27	0.2	77	Kermadec Is.
151	1997.05.15	15:54	5.4	1997.08.18	14:37	5.5	95	55	0.1	60	Tonga Is.
152	1997.06.16	15:40	5.1	1997.06.17	04:59	5.1	0.55	15	0.2	11	S of Kermadec Is.
153	1997.06.17	04:59	5.1	1997.06.18	19:31	5.3	1.6	5.8	0.7	26	S of Kermadec Is.
154	1997.06.18	19:31	5.3	1997.06.19	03:02	5.1	0.3	31	0.1	14	S of Kermadec Is.
155	1997.08.04	18:54	6.1	1997.08.04	19:21	6.0	0.02	25	0.5	16	Tonga Is.
156	1997.08.08	22:27	6.6	1998.01.12	16:36	6.7	157	57	0.5	12	Fiji Is.
157	1998.01.12	16:36	6.7	1998.01.14	17:24	6.6	2.0	32	0.9	19	Fiji Is.
158	1998.03.08	00:00	5.3	1998.03.08	14:01	5.2	0.6	13	0.4	4	Kermadec Is.
159	1998.03.11	19:40	5.6	1998.12.29	11:04	5.6	293	22	0.3	16	Fiji Is.
160	1998.04.20	10:54	5.6	1998.04.23	08:53	5.4	2.9	26	0.2	28	Tonga Is.
161	1998.04.23	08:53	5.4	1998.04.24	19:42	5.4	1.5	17	0.3	33	Tonga Is.
162	1998.08.16	04:48	5.4	1998.10.09	05:37	5.5	54	29	0.2	28	Tonga Is.
163	1998.10.09	05:37	5.5	1999.02.09	10:38	5.4	123	15	0.4	15	Tonga Is.
164	1998.11.24	21:24	5.5	1998.12.11	21:42	5.5	17	49	0.1	18	Samoa Is.
165	1998.12.15	04:07	5.3	1999.05.09	00:35	5.2	145	14	0.3	54	Samoa Is.

166	1999.01.26	12:30	5.7	1999.02.23	18:56	5.5	28	26	0.3	11	Tonga Is.
167	1999.01.29	01:09	5.9	1999.03.07	20:35	6.1	37	11	1.2	9	Fiji Is.
168	1999.03.02	16:54	5.6	1999.04.17	05:11	5.5	45	55	0.1	8	Kermadec Is.
169	1999.07.28	10:08	6.3	1999.08.01	08:39	6.5	3.9	35	0.6	7	Kermadec Is.
170	1999.10.08	05:09	5.8	1999.10.12	13:27	5.6	4.3	9.4	1.0	7	Tonga Is.
171	1999.11.03	23:50	5.6	2000.03.27	17:35	5.5	144	52	0.1	17	Samoa Is.
172	1999.12.25	18:38	5.8	2000.01.20	00:59	5.7	25	30	0.3	13	Kermadec Is.
173	2000.01.17	17:53	5.2	2000.01.18	01:31	5.4	0.3	35	0.2	78	Fiji Is.
174	2000.01.20	00:59	5.7	2000.03.29	07:13	5.8	69	30	0.3	9	Kermadec Is.
175	2000.01.23	22:14	5.5	2000.04.27	08:38	5.4	94	58	0.1	9	Fiji Is.
176	2000.02.28	09:45	5.7	2000.08.17	00:04	5.8	171	48	0.2	9	Tonga Is.
177	2000.03.11	19:54	5.2	2000.03.16	16:08	5.3	4.8	22	0.2	41	Kermadec Is.
178	2000.06.10	08:49	5.5	2000.10.12	02:22	5.4	124	40	0.2	27	Tonga Is.
179	2000.12.28	18:12	5.4	2001.02.27	12:10	5.2	61	25	0.2	11	Tonga Is.
180	2001.01.24	21:07	5.4	2001.03.08	11:37	5.3	43	34	0.2	26	Kermadec
181	2001.02.23	23:52	5.5	2001.08.09	03:09	5.6	166	45	0.2	15	Kermadec
182	2001.03.09	21:41	5.4	2001.03.11	12:37	5.3	1.6	12	0.4	12	Tonga Is.
183	2001.03.11	12:37	5.3	2001.06.13	03:49	5.5	94	16	0.3	5	Tonga Is.
184	2001.06.13	03:49	5.5	2001.06.14	03:55	5.4	1.0	32	0.2	25	Tonga Is.
185	2001.06.16	02:13	6.0	2002.01.28	15:10	6.2	226	73	0.2	28	Samoa Is.
186	2001.07.11	08:53	5.1	2002.01.27	03:04	5.3	200	23	0.2	15	Tonga Is.
187	2001.10.09	20:12	5.3	2001.10.09	20:42	5.2	0.02	14	0.3	9	Tonga Is.
188	2001.11.11	18:27	5.4	2002.05.25	02:35	5.4	194	25	0.2	17	Tonga Is.
189	2001.11.29	19:37	5.4	2002.03.17	10:18	5.2	108	25	0.2	68	Tonga Is.
190	2001.11.30	06:15	5.2	2002.02.14	14:39	5.1	77	23	0.2	66	Tonga Is.
191	2001.11.30	20:24	5.3	2001.11.30	21:08	5.2	0.03	3.3	1.5	3	S of Kermadec Is.
192	2001.12.15	17:34	5.1	2002.04.17	16:42	5.3	123	40	0.1	16	S of Fiji Is.
193	2002.02.08	06:27	5.2	2002.05.04	16:07	5.2	85	27	0.2	75	Tonga Is.
194	2002.02.21	00:30	5.2	2002.06.02	21:47	5.4	102	31	0.2	11	S of Fiji Is.
195	2002.02.21	15:31	5.4	2002.05.18	21:51	5.5	85	47	0.1	2	Fiji Is.
196	2002.03.09	14:09	5.6	2002.04.30	06:25	5.5	51	38	0.2	38	Kermadec Is.
197	2002.03.17	10:18	5.2	2002.06.20	09:04	5.3	95	33	0.1	45	Tonga Is.
198	2002.04.26	02:13	5.5	2002.09.23	22:07	5.4	151	44	0.1	5	Kermadec Is.
199	2002.05.15	03:27	5.9	2003.07.03	06:21	6.0	415	48	0.2	28	Tonga Is.
200	2002.05.18	21:51	5.5	2002.07.22	02:02	5.3	64	26	0.2	25	Fiji Is.
201	2002.06.02	21:47	5.3	2002.06.07	12:09	5.3	4.6	21	0.3	15	S of Fiji Is.
202	2002.06.07	12:09	5.3	2002.08.25	03:52	5.4	79	23	0.2	17	S of Fiji Is.
203	2002.06.25	04:49	5.2	2002.12.28	07:44	5.2	186	34	0.1	29	Tonga Is.
204	2002.10.11	15:16	5.3	2002.10.25	03:49	5.3	13	27	0.2	12	Samoa Is.
205	2002.10.18	21:55	5.4	2002.10.18	22:53	5.4	0.04	20	0.3	30	Fiji Is.
206	2002.11.17	02:58	5.5	2003.03.06	10:24	5.7	109	13	0.6	7	Tonga Is.
207	2003.03.28	17:31	6.2	2003.05.03	05:03	6.2	35	9.7	1.7	15	Tonga Is.
208	2003.04.22	02:03	5.3	2003.07.14	18:19	5.1	84	40	0.1	44	Tonga Is.

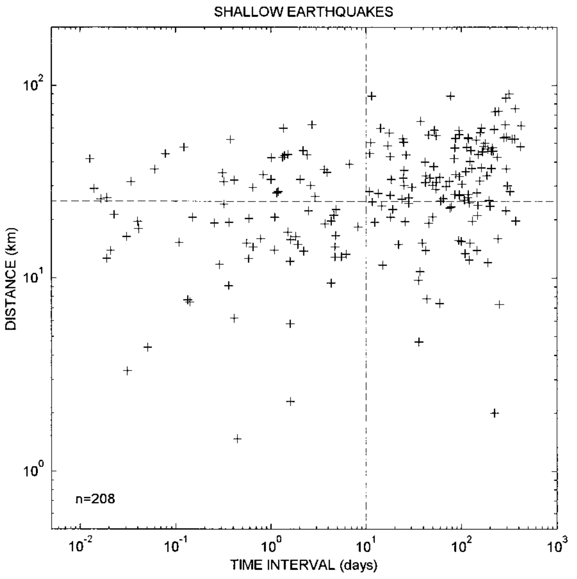

Fig. 10. The distance against the time interval between two events forming a pair for shallow earthquakes. Two dashed lines indicate the distance of 25 km and the time difference of 10 days, respectively.

tend to have greater distances (Figs. 11 and 12). There are 79 pairs with time interval not longer than 10 days (38% of all pairs), and 88 pairs with the distance no more than 25 km (42% of all).

The 3D angle of rotation Φ (Kagan, 1991; 1992) between focal mechanisms of two earthquakes forming a pair, used to study their disorientation, is listed in Table 3. The number of pairs of shallow earthquakes against the rotation angle is shown in

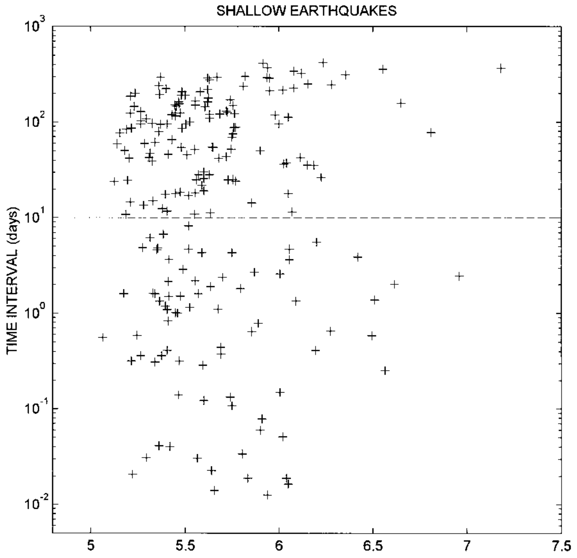

Fig. 11. The time interval between two events forming a pair against their average moment magnitude for shallow earthquakes. The time difference of 10 days is marked by a dashed line.

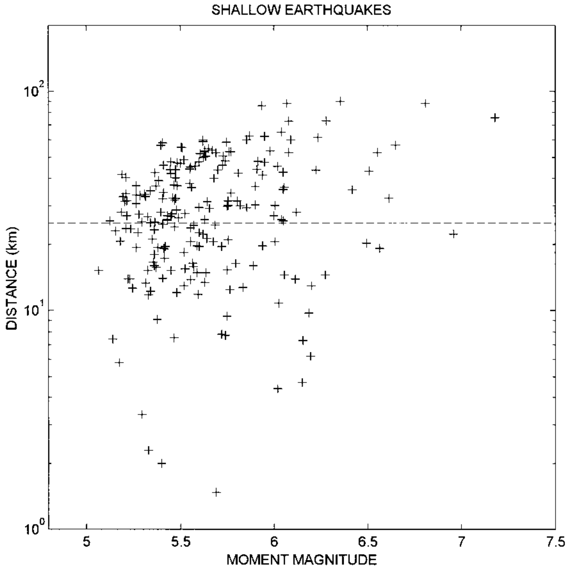

Fig. 12. The distance between two events forming a pair against their average moment magnitude for shallow earthquakes. The distance of 25 km is marked by a dashed line.

Fig. 13. For 157 pairs (75% of all pairs) the rotation angle is less than 30°, and thus both events in these pairs have similar focal mechanism (Kagan and Jackson, 1999). The rotation angle is not dependent on earthquake magnitude. Similarly, the rotation angle seems not to depend on the time interval between two events forming a pair (Fig. 14). It seems, however, to depend to some extend on the distance between the two events (Fig. 15). For the large majority of earthquakes that occur in pairs at a distance not larger than 25 km, the angle of rotation is smaller than 30°.

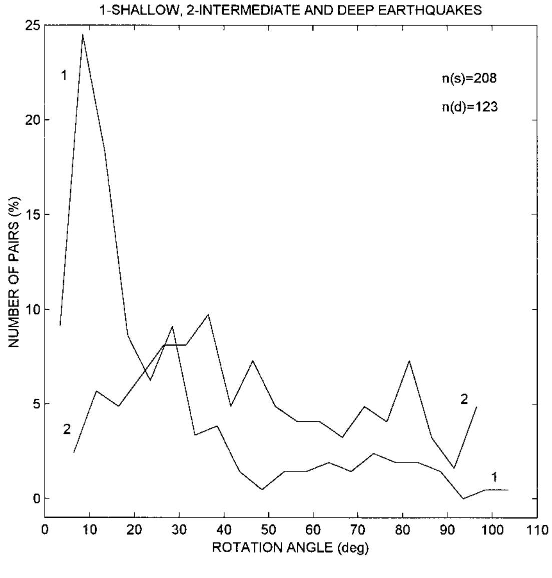

Fig. 13. The number of pairs of shallow (1) and intermediate and deep (2) earthquakes against the rotation angle, that would transform the focal mechanism of one event into that of another event forming a pair, counted in intervals of 5 degrees. The number of pairs for shallow n(s) and deep n(d) events is also given.

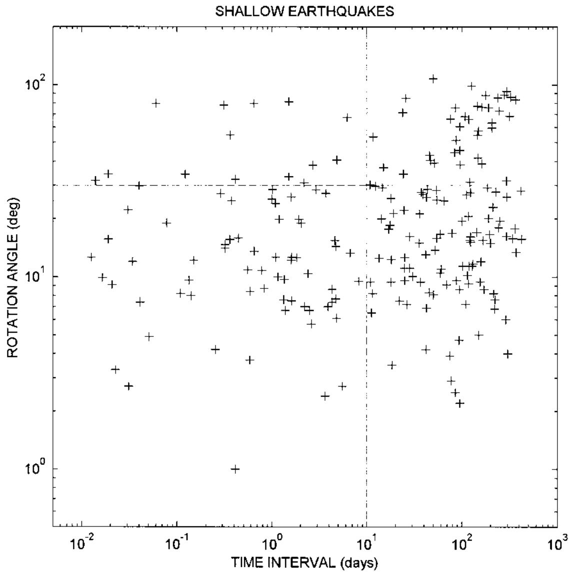

Fig. 14. The rotation angle against the time interval between two events forming a pair for shallow earthquakes. Two dashed lines indicate the rotation angle of 30° and the time difference of 10 days, respectively.

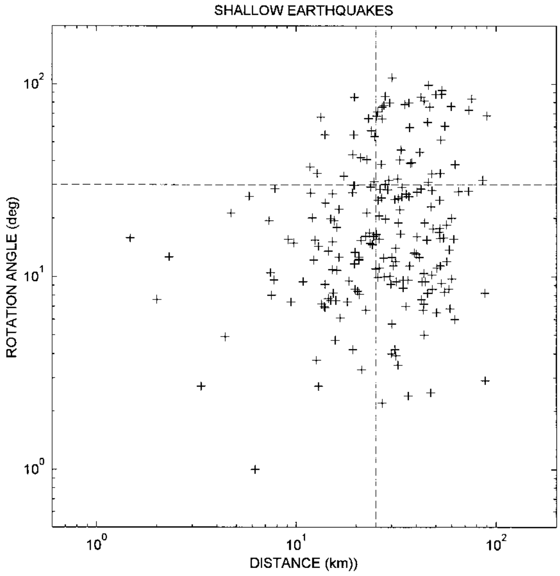

Fig. 15. The rotation angle against the distance between two events forming a pair for shallow earthquakes. Two dashed lines indicate the rotation angle of 30° and the distance of 25 km, respectively.

The degree of fault rupture overlap η in a pair was also calculated and is listed in Table 3. It is the sum of the respective rupture lengths of the two earthquakes forming a pair divided by the double distance between their centroids (Kagan and Jackson, 1999). The rupture lengths were estimated using expressions given by Wells and Coppersmith (1994). The values of η larger than 1.0 suggest that the rupture zones of both earthquakes overlap (Kagan and Jackson, 1999). We have 18 pairs (9% of all pairs) with the η values in excess of 1.0, and 61 pairs (29% of all pairs) with the η not smaller than 0.5. The η values are not distinctly dependent on earthquake magnitude, although they seem to increase with increasing magnitude, and they are not dependent on the time interval between two events forming a pair. The rotation angle, however, is smaller than 30° for all 18 pairs with η larger than 1.0 and for all 61 pairs, except of 3 of them, with η not smaller than 0.5 (Fig. 16).

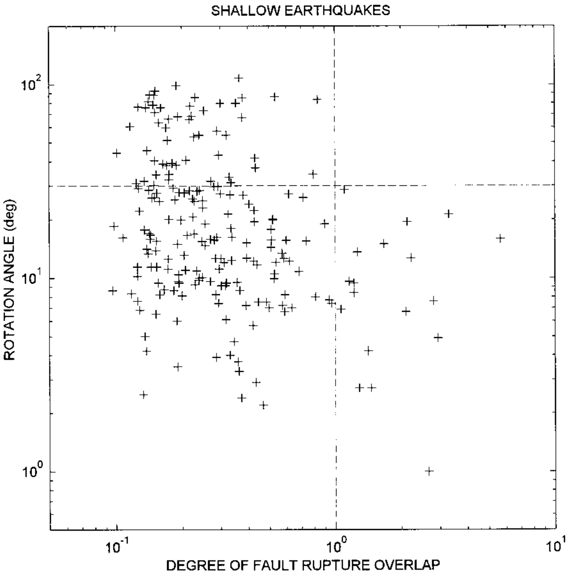

Fig. 16. The rotation angle against the degree of fault rupture overlap between two events forming a pair of shallow earthquakes. Two dashed lines indicate the rotation angle of 30 degrees and the degree of rupture overlap of 1, respectively.

The focal mechanism of all shallow earthquakes is dominated by reverse faulting, clearly observed (with the rake within 30°) for 654 events (64% of all events), whereas normal faulting is observed for 118 events (12% of all), and strike-slip faulting for 93 events (9% of all). Similarly, the focal mechanism of shallow earthquakes associated with doublets and multiplets is distinctly observed as reverse faulting for 276 events (74% of all), as normal faulting for 29 events (8% of all), and as strike-slip faulting for 28 events (8% of all).

6. INTERMEDIATE AND DEEP EARTHQUAKES

It is well known that deep earthquakes display fault-like source processes (e.g., Isacks *et al.*, 1967). Physical models proposed for their occurrence, therefore, should be capable of explaining such behaviour. In the Tonga region there are two principal modes of deformation acting on the subducted lithosphere: the down-dip compression associated with the subducting flow, and the lateral shear involving the whole deep lithosphere, associated with the relative motion between surface plates and deep mantle

(Giardini, 1992). The depth distribution of earthquakes suggests that several mechanisms cause deep events. Cold subducting slabs show a broad peak in seismicity between 300 and 530 km depth that is best explained by transformational faulting of metastable olivine (Estabrook, 2004). Cumulative seismic moment release increases sharply at about a depth of 530 km, implying that deeper events are controlled by an equilibrium rather than metastable phase changes (Estabrook, 2004).

Isacks *et al.* (1967) first observed that a small percentage of deep earthquakes in the Fiji-Tonga-Kermadec region cluster in the form of multiplets, mostly as doublets. Wiens and Snider (2001) have identified in the Tonga slab groups of deep earthquakes with nearly identical waveforms, clustering along a plane 10 to 30 km in length. Some of the earthquakes are collocated, demonstrating repeated rupture of the same fault, and one pair of events shows identical rupture complexity. Wiens and Snider (2001) suggest that runaway thermal shear instabilities may explain temporally clustered earthquakes with similar waveforms located along slip zones weakened by shear heating. Earthquake doublets that occur within a few hours are consistent with events recurring before the thermal energy of the initial rupture can diffuse away.

We have 31 pairs of intermediate earthquakes and 92 pairs of deep earthquakes. Since the number of pairs of intermediate events is limited, we consider intermediate and deep events jointly as deep earthquakes. Thus, we have 123 pairs of deep earthquakes whose centroids are located at a distance ranging from 6.8 to 85 km and whose time separation ranges from 0.018 to 387 days (Tables 4 and 5). The distance against the time interval between two events forming a pair is shown on a logarithmic scale in Fig. 17. The distance of 40 km and time interval of 25 days are marked out to underline the pairs characterized by the smallest distance and shortest time interval. Simi-

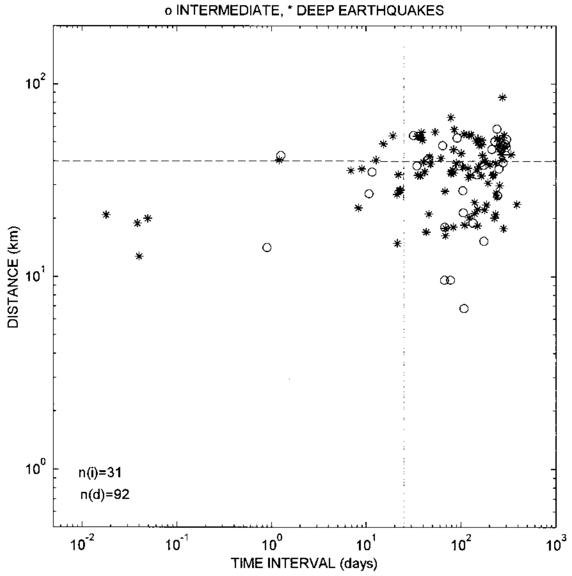

Fig. 17. The distance against the time interval between two events forming a pair for intermediate and deep earthquakes. Two dashed lines indicate the distance of 40 km and the time difference of 25 days, respectively.

Table 4

Pairs of intermediate earthquakes (50 < h < 300 km) from the Harvard CMT catalogue. Δt is the time interval between two events, R is the distance, and Φ is the 3D rotation angle

No.	First event				Second event				Differences			Region
	date y m d	time h m	h [km]	M_w	date y m d	time h m	h [km]	M_w	Δt [day]	R [km]	Φ [deg]	
1	1980.06.18	10:49	73	6.4	1980.08.24	20:10	55	6.3	67	18	23	Tonga Is.
2	1980.07.13	22:13	54	5.8	1980.09.15	23:30	81	5.8	64	48	78	Tonga Is.
3	1980.08.24	20:10	55	6.3	1980.10.09	16:19	60	6.2	46	41	11	Tonga Is.
4	1980.09.15	23:30	81	5.8	1980.09.17	05:07	63	5.7	1.2	43	60	Tonga Is.
5	1984.05.25	02:32	64	5.6	1984.10.19	20:00	92	5.6	148	34	48	Kermadec Is.
6	1984.11.06	09:44	247	5.6	1984.11.18	00:49	230	5.8	12	35	29	Tonga Is.
7	1985.12.17	21:41	201	5.4	1986.03.25	08:00	189	5.4	97	38	21	Fiji Is.
8	1986.04.15	13:15	84	5.5	1986.11.29	16:54	100	5.7	228	50	53	Tonga Is.
9	1986.06.28	05:03	222	6.5	1987.03.19	22:51	215	6.6	265	46	14	Fiji Is.
10	1987.03.19	22:51	215	6.6	1988.01.15	08:40	221	6.4	301	47	85	Fiji Is.
11	1987.06.16	20:17	132	5.6	1988.01.13	15:38	143	5.6	212	46	34	S of Fiji Is.
12	1987.12.25	22:56	205	5.9	1988.10.23	00:23	217	5.7	292	49	19	Fiji Is.
13	1989.02.07	12:41	110	5.4	1989.03.13	03:37	92	5.2	35	38	97	Kermadec Is.
14	1989.03.16	09:34	55	5.9	1989.09.07	13:32	51	5.9	174	15	15	Kermadec Is.
15	1991.02.28	13:30	225	5.8	1991.06.13	17:18	205	5.9	105	28	36	Tonga Is.
16	1992.06.07	14:26	67	6.3	1992.10.20	15:48	73	5.5	134	19	13	S of Fiji Is.
17	1994.02.23	18:00	124	5.9	1994.02.24	15:25	128	6.1	0.9	14	4	Tonga Is.
18	1994.05.19	17:53	255	5.7	1995.01.14	06:49	215	5.7	240	58	55	Kermadec Is.
19	1995.03.24	07:11	130	5.6	1995.06.23	16:11	114	5.8	91	53	94	S of Fiji Is.
20	1996.03.06	01:35	146	5.8	1997.01.03	03:58	147	6.0	303	52	52	Tonga Is.
21	1997.11.27	07:21	230	5.4	1998.09.02.	18:52	206	5.5	278	48	58	Kermadec Is.
22	1998.05.17	16:17	66	5.4	1998.09.01	14:33	73	5.5	108	6.8	88	Tonga Is.
23	1998.12.27	00:38	160	6.8	1999.04.13	10:38	173	6.8	106	21	9	Fiji Is.
24	1999.12.07	21:29	149	6.4	2000.09.11	17:18	125	6.3	279	39	60	Tonga Is.
25	2000.01.26	13:27	69	6.3	2000.09.26	06:17	70	6.4	245	26	48	Tonga Is.
26	2000.05.07	08:47	61	5.7	2000.10.29	12:30	54	5.8	175	38	82	Tonga Is.
27	2000.09.16	17:26	54	5.5	2000.10.17	10:33	52	5.4	32	54	51	Kermadec Is.
28	2000.10.29	12:30	54	5.8	2000.11.09	05:46	69	5.8	11	27	70	Tonga Is.
29	2001.07.20	00:21	76	5.4	2001.10.05	17:54	68	5.3	78	9.6	32	Tonga Is.
30	2001.10.28	20:24	186	5.7	2002.08.07	04:50	179	5.8	252	36	19	Fiji Is.
31	2002.12.05	17:28	141	5.4	2003.02.09	14:00	142	5.4	67	9.6	38	Tonga Is.

Table 5

Pairs of deep earthquakes ($h \geq$ 300 km) from the Harvard CMT catalogue.
Δt is the time interval between two events, R is the distance, and Φ is the 3D rotation angle

No.	First event				Second event				Differences			Region
	date y m d	time h m	h [km]	M_w	date y m d	time h m	h [km]	M_w	Δt [day]	R [km]	Φ [deg]	
1	1977.01.05	13:29	562	5.7	1977.03.14	19:03	579	5.8	68	28	38	Fiji Is.
2	1977.01.14	17:58	358	5.5	1977.05.22	23:27	347	5.7	129	54	43	Fiji Is.
3	1977.03.08	03:02	574	5.6	1977.05.25	12:10	598	5.8	78	35	22	Fiji Is.
4	1977.04.22	23:11	554	5.3	1977.06.03	14:33	565	5.4	42	35	68	Fiji Is.
5	1978.05.03	23:50	516	5.4	1978.10.17	22:56	547	5.4	167	49	39	Fiji Is.
6	1978.08.17	08:32	608	5.8	1978.12.21	00:35	613	5.9	127	34	55	Fiji Is.
7	1978.10.16	23:55	567	5.7	1979.07.24	09:22	556	5.8	280	18	71	Fiji Is.
8	1979.07.08	08:55	600	5.3	1979.11.25	11:38	593	5.4	140	21	25	Tonga Is.
9	1979.08.23	00:25	576	5.4	1979.08.29	21:29	551	5.3	6.9	36	24	Fiji Is.
10	1979.08.23	00:25	576	5.4	1979.11.09	14:38	588	5.5	79	34	30	Fiji Is.
11	1980.01.15	04:25	608	5.5	1980.01.30	11.29	609	5.4	15	49	45	Fiji Is.
12	1980.02.13	20:38	605	5.6	1980.10.02	15:49	592	5.6	232	21	82	Fiji Is.
13	1980.02.18	17:17	615	5.8	1980.06.17	08:43	602	5.8	120	33	46	Fiji Is.
14	1980.06.17	08:43	602	5.8	1980.10.03	01:53	559	6.0	107	55	37	Fiji Is.
15	1981.08.30	11:36	618	5.4	1982.01.01	10:53	610	5.6	122	20	36	Fiji Is.
16	1982.09.17	13:28	562	6.1	1983.06.20	05:43	562	6.2	275	85	96	S of Fiji Is.
17	1983.05.02	09:58	605	5.9	1983.05.03	15:39	592	5.9	1.2	40	79	Fiji Is.
18	1983.05.03	15:39	592	5.9	1983.12.24	18:21	607	5.7	235	27	76	Fiji Is.
19	1983.09.16	08:09	517	6.0	1984.03.12	10:50	556	6.2	179	40	34	S of Fiji Is.
20	1983.12.08	11:01	599	5.7	1984.01.17	19:50	597	5.6	40	40	45	S of Fiji Is.
21	1984.01.20	03:53	545	5.6	1984.07.03	13:42	533	5.7	165	33	81	Fiji Is.
22	1984.09.15	10:59	593	5.3	1984.10.20	21:22	594	5.5	35	34	86	Fiji Is.
23	1985.01.30	16:29	614	5.3	1985.04.02	03:21	637	5.3	62	41	98	Fiji Is.
24	1986.08.06	09:54	558	5.3	1986.11.18	22:48	541	5.4	104	37	23	S of Fiji Is.
25	1986.09.06	20:04	593	5.7	1987.05.03	16:46	591	5.7	239	26	82	Fiji Is.
26	1986.11.06	00:16	597	5.8	1987.02.14	13:38	578	5.7	100	44	56	Fiji Is.
27	1986.11.18	22:48	541	5.4	1986.12.26	07:03	540	5.3	37	33	31	S of Fiji Is.
28	1987.02.10	00:59	418	6.5	1987.04.29	14:27	411	6.5	78	67	76	Fiji Is.
29	1987.07.29	20:37	645	5.7	1987.07.29	21:32	654	5.7	0.04	19	10	Fiji Is.
30	1987.09.01	22:46	613	5.4	1987.09.24	06:03	614	5.5	23	28	20	Fiji Is.
31	1988.01.24	16:00	583	5.9	1988.03.04	03:08	599	5.9	39	51	35	Fiji Is.
32	1988.04.11	22:36	621	5.5	1988.07.04	08:28	625	5.3	84	46	36	Fiji Is.
33	1988.05.28	16:27	576	5.7	1988.07.06	01:10	549	5.9	38	56	88	Fiji Is.
34	1988.09.11	06:17	527	5.5	1989.04.25	00:31	520	5.3	226	20	25	S of Fiji Is.
35	1988.11.16	05:53	623	5.8	1989.05.04	13:15	616	5.7	169	43	44	Fiji Is.
36	1989.04.30	15:34	591	6.0	1989.05.21	21:56	599	5.9	22	27	26	Fiji Is.

37	1989.10.23	13:08	480	6.1	1989.11.29	05:49	516	6.1	37	53	25	S of Fiji Is.
38	1989.10.30	23:46	586	5.8	1990.06.19	19:07	614	5.6	233	39	17	Fiji Is.
39	1990.01.01	07:49	627	5.4	1990.01.09	14:43	623	5.3	8.3	23	35	Fiji Is.
40	1990.01.18	20:57	593	5.7	1990.06.19	19:07	614	5.6	152	52	26	Fiji Is.
41	1990.02.02	18:34	590	5.8	1990.07.08	16:30	564	5.9	156	48	50	Fiji Is.
42	1990.04.13	08:16	581	5.5	1990.10.14	01:58	552	5.3	183	39	51	Fiji Is.
43	1990.07.11	19:49	590	6.0	1991.01.14	14:12	600	5.9	187	24	6	S of Fiji Is.
44	1990.10.21	19:05	518	5.3	1991.03.21	20:08	523	5.4	151	18	60	Fiji Is.
45	1990.11.03	14:18	610	5.3	1991.05.20	09:50	600	5.5	168	51	28	Fiji Is.
46	1990.11.29	00:40	634	5.6	1990.12.07	23:08	617	5.4	9.0	36	64	Fiji Is.
47	1991.07.15	15:57	514	5.3	1991.08.22	13:18	529	5.4	38	53	33	S of Fiji Is.
48	1991.08.09	20:16	456	5.5	1991.09.25	17:43	433	5.4	47	42	96	S of Fiji Is.
49	1991.08.22	13:18	529	5.4	1991.12.19	21:01	550	5.6	119	37	88	S of Fiji Is.
50	1991.08.27	08:51	618	5.4	1991.10.14	14:36	597	5.4	48	38	33	Fiji Is.
51	1992.08.30	20:09	574	6.4	1993.03.21	05:05	608	6.3	202	38	37	Fiji Is.
52	1992.09.15	02:28	587	5.7	1993.04.20	16:26	600	5.8	217	33	66	Fiji Is.
53	1992.11.21	18:27	378	5.5	1993.09.04	08:31	396	5.5	287	54	83	Fiji Is.
54	1992.12.20	16:38	513	5.5	1993.09.16	06:51	507	5.3	270	43	39	S of Fiji Is.
55	1993.01.19	21:14	625	5.4	1993.03.13	03:03	649	5.5	54	56	75	Fiji Is.
56	1993.07.23	16:38	649	5.6	1993.08.05	12:42	633	5.6	13	40	71	Fiji Is.
57	1993.08.05	12:42	633	5.6	1993.10.27	21:16	641	5.8	85	58	83	Fiji Is.
58	1994.04.24	02:41	594	5.7	1994.07.02	05:47	577	5.6	69	18	14	Fiji Is.
59	1994.07.02	05:47	577	5.6	1994.07.02	06:43	583	5.5	0.04	13	9	Fiji Is.
60	1995.02.25	21:54	594	5.7	1995.06.16	13:49	593	5.7	110	18	98	Fiji Is.
61	1995.06.26	06:48	594	5.3	1996.02.01	04:21	583	5.4	220	34	38	Fiji Is.
62	1995.08.25	14:25	558	5.5	1996.06.13	06:58	553	5.6	293	47	42	Fiji Is.
63	1996.02.01	04:21	583	5.4	1996.04.24	09:36	573	5.3	83	18	44	Fiji Is.
64	1996.08.27	06:24	598	5.9	1996.11.17	21:11	602	6.0	83	36	63	S of Fiji Is.
65	1996.10.07	09:24	600	5.5	1997.07.05	23:21	607	5.3	272	40	47	S of Fiji Is.
66	1996.11.30	22:14	617	5.5	1997.01.04	16:51	628	5.4	35	54	34	Fiji Is.
67	1997.03.11	03:14	557	5.7	1997.11.29	02:42	581	5.7	263	44	75	Fiji Is.
68	1997.12.26	05:34	600	5.9	1998.04.28	15:44	618	5.7	122	54	30	Fiji Is.
69	1998.01.27	02:14	651	6.0	1998.10.11	12:04	638	5.9	257	30	70	Fiji Is.
70	1998.01.27	19:55	617	6.3	1998.01.27	21:05	629	6.4	0.05	20	68	S of Fiji Is.
71	1998.06.12	20:51	508	5.5	1998.12.22	22:07	513	5.6	193	31	25	S of Fiji Is.
72	1998.10.26	02:35	583	5.3	1998.11.17	17:08	586	5.4	23	28	10	Fiji Is.
73	1998.11.17	17:08	586	5.4	1999.02.10	09:22	572	5.2	84	35	21	Fiji Is.
74	1999.03.23	11:23	584	5.6	1999.11.30	20:10	557	5.8	252	48	40	Fiji Is.
75	1999.12.11	14:38	579	5.7	2000.01.02	12:14	611	5.5	22	34	84	Fiji Is.
76	2000.01.02	12:14	611	5.5	2000.04.01	12:13	576	5.6	90	39	80	Fiji Is.
77	2000.01.13	20:07	565	6.2	2000.02.28	22:15	563	6.0	46	21	13	Fiji Is.
78	2000.03.01	04:21	686	5.8	2000.03.01	04:46	688	5.6	0.02	21	70	Fiji Is.
79	2000.04.01	12:10	607	5.5	2000.09.02	10:19	621	5.7	154	37	59	Fiji Is.

80	2000.04.17	04:25	560	5.6	2000.12.29	23:33	588	5.4	257	52	101	S of Fiji Is.
81	2001.05.23	15:35	588	5.6	2001.07.31	06:57	576	5.5	69	16	26	Fiji Is.
82	2001.07.31	06:57	576	5.5	2001.12.29	00:09	592	5.6	151	22	29	Fiji Is.
83	2001.09.12	08:48	634	6.4	2002.10.04	19:05	651	6.3	387	24	10	Fiji Is.
84	2002.01.04	08:44	635	5.5	2002.06.30	19:51	650	5.3	177	22	85	S of Fiji Is.
85	2002.01.09	01:03	498	5.4	2002.09.07	10:40	503	5.5	241	52	30	S of Fiji Is.
86	2002.05.04	07:00	580	5.7	2002.06.16	06:55	588	5.9	43	17	58	Fiji Is.
87	2002.06.16	06:55	588	5.9	2003.05.19	10:43	579	5.9	337	43	40	Fiji Is.
88	2002.06.30	19:51	650	5.3	2002.11.16	20:44	635	5.4	139	24	92	S of Fiji Is.
89	2002.08.25	04:42	566	5.5	2003.01.20	18:43	561	5.6	149	36	47	Fiji Is.
90	2002.11.14	11:05	569	5.6	2002.12.03	20:14	584	5.6	19	54	50	Fiji Is.
91	2002.12.03	20:14	584	5.6	2002.12.25	08:54	585	5.5	22	15	48	Fiji Is.
92	2003.02.13	15:38	607	5.5	2003.07.07	16:30	606	5.4	144	51	24	S of Fiji Is.

larly as for shallow events, the distance of 40 km is directly related to the location accuracy taking into account the depth of earthquakes, and the time interval of 25 days was selected from the distribution of time intervals as a function of time. We have 17 such pairs, that is 14% of all pairs. We have, on the other hand, 47 pairs (38% of all pairs) with time intervals longer than 25 days and distances larger than 40 km. In general, the number of all pairs of deep earthquakes is almost twice smaller than that of shallow earthquakes, although the number of all shallow and deep events is approximately the same (Table 1). The relative number of pairs of deep earthquakes with the shortest distance and time interval is also considerably smaller than that of shallow events.

The time interval and the distance between two deep events forming a pair is not dependent on their average magnitude, similarly as in the case of shallow earthquakes. There are 20 pairs (16% of all pairs) with time interval not longer than 25 days, and 73 pairs (59% of all pairs) with the distance not larger than 40 km.

The time interval and the distance between two events forming a pair against their average depth are shown in Figs. 18 and 19. We have 20 pairs (16% of all pairs) with the time interval not longer than 25 days, and 73 pairs (59% of all) with the distance not larger than 40 km. The pairs with the shortest time separations appear at the greatest depth (Fig. 18), and the pairs with the smallest distances occur at the smallest and at the greatest depths (Fig. 19). The number of all earthquakes and those associated with doublets and multiplets as a function of depth is shown in Fig. 20. The well-known maximum at a depth of about 600 km (e.g., Isacks *et al.*, 1967; Zarifi and Havskov, 2003) is apparent. The secondary maximum in the distribution of all events appears at a depth of about 380 km. The distribution of associated earthquakes is similar to that of all earthquakes, except that the secondary maximum is absent.

The relative number of deep earthquakes associated with doublets and multiplets increases sharply with depth. The ratio of the number of associated events over the

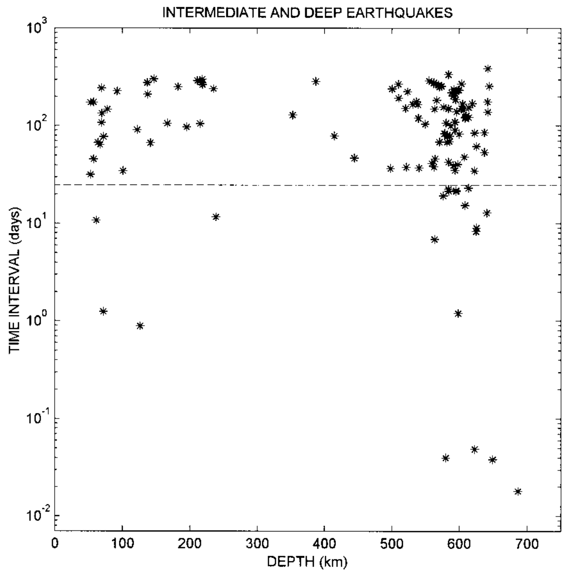

Fig. 18. The time interval between two events forming a pair against their average depth for intermediate and deep earthquakes. The time difference of 25 days is marked by a dashed line.

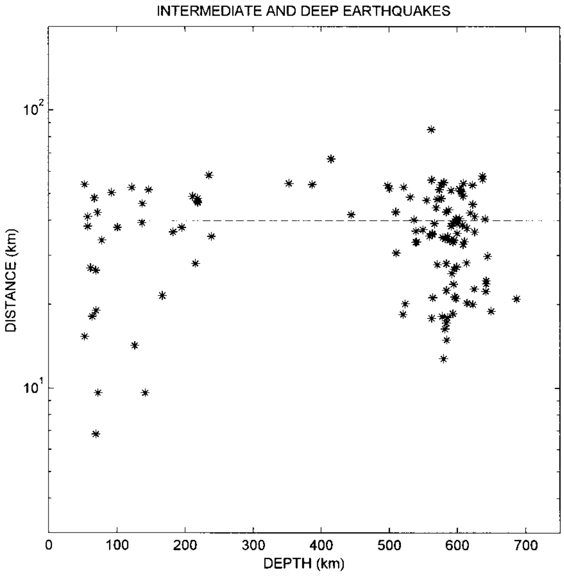

Fig. 19. The distance between two events forming a pair against their average depth for intermediate and deep earthquakes. The distance of 40 km is marked by a dashed line.

number of all events against their depth is shown in Fig. 21. The ratio increases from 5-10% to 40-45% between the depth from 370 to 600 km. It seems that at this depth range special conditions are present which favour the occurrence of earthquake multiplets.

The 3D rotation angle *Φ* (Kagan, 1991) between focal mechanisms of two earthquakes forming a pair is listed in Tables 4 and 5. It is not dependent on earthquake

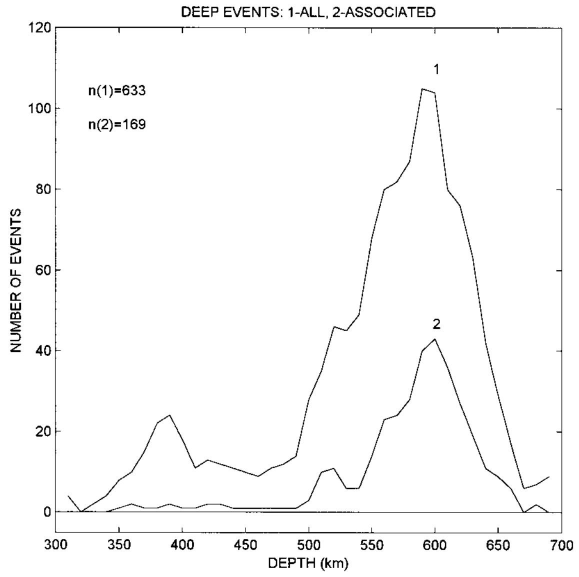

Fig. 20. The number of all (1) and associated (2) with doublets and multiplets deep earthquakes against their depth. The number of events was counted for each depth window of 20 km, moved every 10 km. The total number of events is also given.

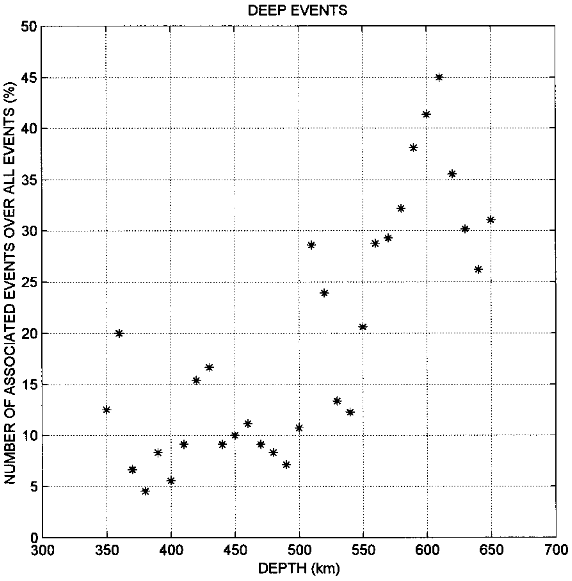

Fig. 21. The ratio of the number of events associated with doublets and multiplets over the number of all events (in %) against their depth for deep earthquakes. The number of events was counted for each depth window of 20 km, moved every 10 km.

magnitude, and time and distance separations between two events in a pair. The rotation angle as a function of depth is shown in Fig. 22. For 37 pairs (30% of all pairs) the rotation angle is less than 30° in contrast to the shallow earthquakes, whose 75% of all pairs are characterized by small rotation angles. Ellis and Davis (1994) found that earthquake doublet mechanisms are more diverse in deep regions than along plate boundaries. More than 50% of their deep events required more than 50° of rotation

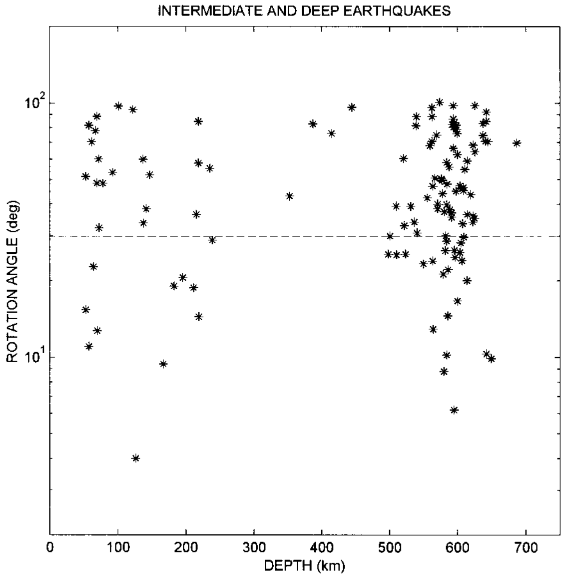

Fig. 22. The rotation angle that would transform the focal mechanism of one event into that of another event forming a pair against the average depth of a given pair for intermediate and deep earthquakes. The rotation angle of 30 degrees is marked by a dashed line.

that would transform the focal mechanism of one event into that of another event forming a pair. Ellis and Davis (1994) attribute the diverse mechanisms in deep doublets to the accommodation of 3D deformation, resulting from the absence of a single predominant fault.

The focal mechanism of all intermediate and deep earthquakes is dominated to some extend by normal faulting, distinctly observed for 417 events (40% of all events). Reverse faulting is observed for 270 events (26% of all) and strike-slip mechanism appears in 9 cases (1% of all) only. Similarly, the focal mechanism of deep earthquakes associated with doublets and multiplets is characterized by normal faulting in 84 events (37% of all events), by reverse faulting in 65 events (29% of all), and by strike-slip faulting in 1 case only.

7. CONCLUSIONS

1. Earthquake doublets and multiplets in the Fiji-Tonga-Kermadec region are often observed at all depths and within the whole magnitude range. The earthquakes associated with doublets and multiplets constitute 36% of all shallow events, 14% of all intermediate events, and 27% of all deep events.

2. The non-randomness of the occurrence of shallow earthquakes forming the pairs is confirmed by thorough statistical analysis. Limited number of deep doublets prevents the application of similar analysis to deeper events.

3. Shallow earthquakes tend to form the pairs at smaller distances and with shorter time separations than deep earthquakes. The pairs of deep earthquakes with the

shortest time intervals appear at the greatest depths. The relative number of deep earthquakes associated with doublets and multiplets increases sharply with depth.

4. A comparison of focal mechanism of earthquakes forming pairs, measured by the 3D rotation angle, shows that deep earthquakes have more diverse focal mechanism than the shallow events. The rotation angle for three quarters of pairs of shallow earthquakes and only for about one third of deep earthquakes is smaller than 30°, implying that both events in these pairs have similar focal mechanisms. The focal mechanism of shallow events corresponds to distinct reverse faulting in about three quarters of the cases, whereas the deep earthquakes show distinct both reverse and normal faulting in about one third of the cases.

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