

Article

Relationships of Seismic Source Parameters and Magnitude for $M_w \geq 7.0$ Earthquakes

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Abstract

Literature-based compilation indicates that there have been 165 earthquakes with moment magnitude $M_w \geq 7.0$ in the period 1980–2024 for which identifiable source-parameter estimates are available. Despite the relative scarcity of such events globally, this dataset is sufficiently large to perform a robust rupture analysis. Using ordinary least-squares regression, we characterized the relationships between M_w and eight source parameters: rupture length (L), rupture width (W), rupture area (S), maximum slip ($D_{\max}$), average slip ($\bar{D}$), average rupture velocity (V_r), source-averaged static stress drop ($\Delta\sigma$), and rupture duration (T_R). The logarithms of rupture length, width, area, maximum slip, and average slip generally showed statistically significant linear relationships with M_w . In contrast, average rupture velocity and static stress drop showed weak and mostly statistically insignificant relationships with M_w . Rupture duration was more strongly correlated with M_w for reverse/thrust- and normal-fault earthquakes than for strike-slip earthquakes. Strike-slip earthquakes had a mean length-to-width ratio of 3.97, compared with 2.05 and 2.43 for reverse/thrust- and normal-fault earthquakes, respectively. For the 25 events with both maximum- and average-slip estimates, the ratio $D_{\max}/\bar{D}$ ranged mainly from 1.5 to 3.5, with a mean of 3.18, indicating spatially heterogeneous slip distributions. Because the dataset was compiled from studies using different source models and inversion methods, the resulting equations should be interpreted as dataset-specific empirical relationships.

Keywords: large earthquakes; source parameters; moment magnitude; rupture scaling; faulting mechanism



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1. Introduction

Large earthquakes can cause substantial casualties, economic losses, and secondary hazards such as landslides and tsunamis [1]. Moment magnitude (M_w) is the standard measure of earthquake size, whereas source parameters such as rupture length, rupture width, rupture area, and fault slip describe the geometry and kinematics of the rupture process. Quantifying the relationships between these parameters and M_w is important for earthquake-source characterization and seismic-hazard assessment.

Traditionally, seismologists have explored the nature of earthquakes through the analysis of source parameters, magnitude determination, and seismic wave propagation characteristics. Nonetheless, the precise relationships between earthquake source parameters and

magnitude continue to be a pivotal issue in seismological research. A comprehensive understanding of these relationships not only enhances our insight into the source processes of earthquakes but also refines the calibration of source parameters. This, in turn, optimizes risk assessment and improves the capacity for responding to earthquake hazards. In recent years, researchers have sought to elucidate the impact of various source parameters on earthquake magnitude and to establish empirical relationships through statistical methods. However, variations in data sources, estimation techniques for rupture parameters, and the geographical areas studied, combined with factors such as earthquake type and fault slip mechanisms, contribute to issues of applicability and discrepancies among established empirical formulas. For instance, Somerville et al. [2] analyzed a limited set of finite-fault rupture models to characterize rupture dimensions, average slip, maximum slip, and spatial slip distributions. Their study quantified source-scaling and slip-distribution characteristics for shallow crustal earthquakes, although the available dataset was limited and the scaling relationships were not developed separately for all faulting mechanisms. Mai and Beroza [3] analyzed 31 finite-fault models from 18 earthquakes using spatial autocorrelation functions and compared strike-slip and dip-slip events. Their results described the spatial complexity of earthquake slip, although the number of available rupture models was limited. Wells and Coppersmith [4] compiled data on shallow earthquakes with magnitudes of 4.5 or higher from published surface fault observations and seismic surveys, classifying the events as strike-slip, reverse, or normal faulting. Notably, they reported both mechanism-specific and combined regression relationships, employing least squares to calculate the regression equations. This approach, combined with uncertainties in the measurement of subsurface rupture parameters, compromises the reliability of the resulting equations. Blaser et al. [5] identified distinct scaling relationships for different slip-type earthquakes, noting that continental and subduction zone retroflex fault earthquakes exhibited similar scaling patterns. Thingbaijam et al. [6] developed empirical source-scaling relationships for rupture length, width, area, and average slip using the systematically compiled SR-CMOD database, which covers earthquakes of M_w 5.4–9.2 and multiple faulting styles. Unlike most previous studies based on ordinary least-squares regression, they applied general orthogonal regression to account for uncertainties in all variables and to obtain mutually self-consistent scaling relationships. However, they did not investigate other rupture parameters beyond those related to scaling. Yin [7] compiled rupture parameters from 91 earthquakes across mainland China and neighboring regions, calculating these parameters using least-squares regression. While they derived a magnitude-rupture scale relationship, the overall sample size remains small, and the analysis is limited to classifying faults into strike-slip and dip-slip types, neglecting a broader spectrum of fault models. Allen and Hayes [8] provided rupture-scale relationships for parameters such as rupture area, length, width, maximum slip, and average slip by analyzing subduction zone interface earthquakes and other global submarine seismic events. However, their study did not address critical parameters like stress drop and rupture velocity. Ding et al. [9] utilized a least squares fitting method to derive the relationship between magnitude and fault slip scale, drawing from a finite fault model of 195 strong earthquakes with magnitudes of 7.0 or higher. However, their analysis did not encompass other rupture parameters, such as the total amount of fault slip, limiting the comprehensiveness of their findings.

Although earthquake source-scaling relationships have been studied extensively, previous datasets commonly span broad magnitude ranges, focus on particular tectonic environments, or include only a subset of source parameters. The present study provides an updated literature-based statistical characterization of 165 $M_w \geq 7.0$ earthquakes (the source parameters are obtained from the published literatures summarized in the Supplementary Materials) that occurred between 1980 and 2024. We jointly examine rup-

ture length, rupture width, rupture area, maximum slip, average slip, rupture velocity, static stress drop, and rupture duration. We compare their relationships with M_w among strike-slip, reverse/thrust-, and normal-fault earthquakes and examine selected relationships among the source parameters. This study does not propose a fundamentally new scaling theory. Its contribution is the integrated analysis of multiple source parameters within a consistently organized compilation of large earthquakes. Because the events were selected according to the availability of published source models, the resulting relationships should not be interpreted as statistically representative of all global $M_w \geq 7.0$ earthquakes.

2. Data and Methodology

The USGS Earthquake Catalog lists 637 earthquakes with $M_w \geq 7.0$ between 1 January 1980 and 31 December 2024 (<https://earthquake.usgs.gov/fdsnws/event/1/>; accessed on 8 October 2024). We searched published studies for source-parameter estimates associated with these events. An event was included when at least one of the source parameters examined in this study could be traced to an identifiable publication. This procedure yielded a literature-based compilation of 165 earthquakes (Figure 1). Events without traceable source-parameter estimates were excluded. No missing parameter was assigned a value of zero or statistically imputed; therefore, the effective sample size differs among parameters and regression analyses. Because the availability of published source models varies with earthquake magnitude, date, location, and societal impact, the selected events may be affected by publication and selection biases and should not be considered a statistically representative subset of all 637 earthquakes.

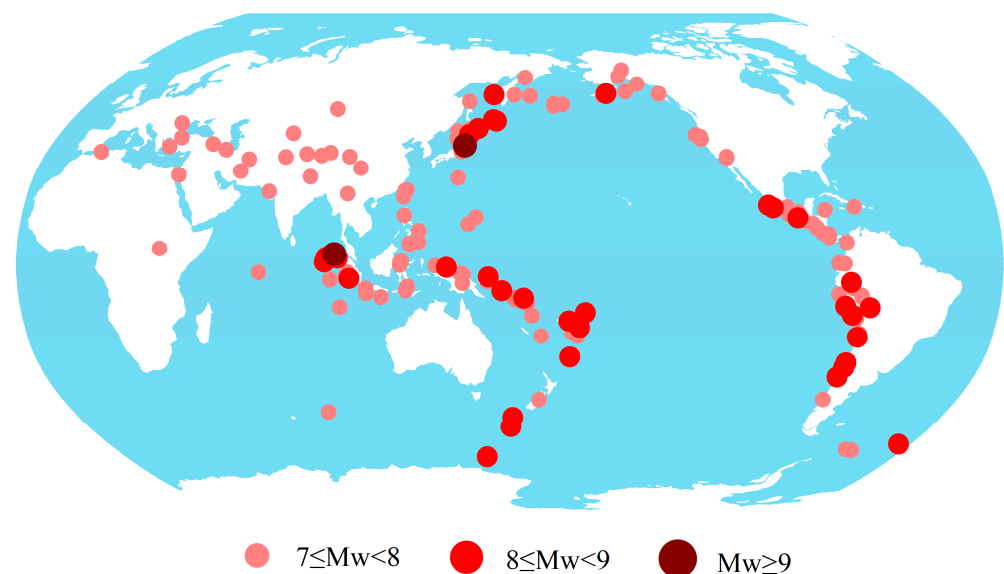


Figure 1. Distribution of the 165 seismic events with moment magnitudes (M_w) ≥ 7.0 .

When several source models were available for the same earthquake, preference was given to a publication that reported multiple source parameters within a consistent model. When no single publication provided all required parameters, estimates from additional identifiable studies were used. The source selected for each event and parameter is documented in Supplementary Table S2. No averaging of multiple published models was performed unless explicitly stated.

Source-parameter estimates were compiled from published field investigations and source-inversion studies. Supplementary Table S1 summarizes the ranges and effective sample sizes of the parameters used in the regression analyses. Supplementary Table S2 reports the event-specific parameter values, estimation methods, and corresponding references. Missing values were retained as missing and were excluded only from analyses requiring the relevant parameter.

Seismic moment is defined as $M_0 = \mu A \bar{D} = \mu L W \bar{D}$, where μ is the shear modulus, A is rupture area, L and W are rupture length and width, respectively, and $\bar{D}$ is average slip. Moment magnitude is calculated from the logarithm of seismic moment. Consequently, the relationships of M_w with L , W , A , and $\bar{D}$ are not completely independent empirical correlations but are partly constrained by the physical definition of seismic moment.

The source parameters were log10-transformed when a log-linear scaling form was used. Ordinary least-squares regression was applied to estimate each transformed source parameter conditional on M_w . This approach permits comparison with previously published OLS relationships but treats M_w as an error-free predictor and does not explicitly account for uncertainty in both variables. In contrast, Thingbaijam et al. [6] used general orthogonal regression to account for errors in both variables and to obtain mutually consistent scaling relationships. Because uniform event-specific uncertainty estimates were unavailable in the compiled studies, uncertainty-weighted orthogonal regression could not be applied consistently. The equations presented here should therefore be interpreted as dataset-specific predictive relationships.

In this study, $\Delta\sigma$ denotes source-averaged static stress drop, defined as the average decrease in shear stress over the rupture area. Apparent stress, dynamic stress drop, breakdown stress drop, and local peak stress-drop estimates were excluded. Static stress-drop values were nevertheless estimated using different approaches in the original studies, including spectral, rupture-dimension-based, and finite-fault methods. This methodological heterogeneity may increase the scatter of the $\Delta\sigma$ – M_w relationship. The definition, estimation method, and source of each retained value are reported in Supplementary Table S2.

Prior research indicates that the source mechanism influences the correlation between source parameters and magnitude. Different methods, such as waveform inversion, P-wave initial motion solutions, and moment tensor inversion, can yield varying results for the source mechanisms of seismic events. Generally, the source mechanisms derived from long-period P-wave and SH-waveform inversions are regarded as more representative of the primary features of coseismic sliding, thus they are preferred over short-period P-wave initial motion solutions [10]. In this study, we systematically classify the source mechanisms of the examined earthquakes and categorize their originating faults into three types: normal faults (NO), reverse thrust faults (TH), and strike-slip faults (SS). The 165 events comprise 96 reverse/thrust-, 48 strike-slip-, and 21 normal-fault earthquakes. Faulting mechanism and tectonic setting are treated as separate classifications: the former describes the rupture mechanism, whereas the latter distinguishes subduction-interface, intraslab/outer-rise, crustal interplate, and crustal intraplate environments.

3. Statistical Analysis of Source Parameters

For the collected seismic source parameters of 165 strong earthquakes of magnitude 7 or above, the least squares method was used to establish the empirical relationship equations between the fault length, width, area, maximum slip, average slip, average rupture velocity, stress drop, and duration of rupture and moment magnitude, and the fitting results are shown in Table 1.

Table 1. Rupture scale parameters derived from least squares fitting (1980–2024).

Equation	Slip Type	Coefficients and Standard Errors				Correlation Coefficient r	Magnitude Range	Effective Number of Earthquake Events
		$a(sa)$	95% CI for a	$b(sb)$	95% CI for b			
$\lg(L) = a + b \times M_w$	ALL	−2.31(0.39)	[−3.07, −1.55]	0.55(0.05)	[0.45, 0.65]	0.67	7.0–9.0	146
	SS	−1.61(0.96)	[−3.49, 0.27]	0.47(0.13)	[0.22, 0.72]	0.53	7.0–8.6	38
	TH	−2.82(0.54)	[−3.88, −1.76]	0.62(0.07)	[0.48, 0.76]	0.70	7.0–9.0	88
	NO	−1.76(0.60)	[−2.94, −0.58]	0.48(0.08)	[0.32, 0.64]	0.82	7.0–8.4	20
$\lg(W) = a + b \times M_w$	ALL	−1.48(0.41)	[−2.28, −0.68]	0.41(0.05)	[0.31, 0.51]	0.56	7.0–9.0	131
	SS	−0.54(1.02)	[−2.54, −1.46]	0.27(0.13)	[0.02, 0.52]	0.36	7.0–8.6	31
	TH	−1.90(0.51)	[−2.90, −0.90]	0.47(0.07)	[0.33, 0.61]	0.63	7.0–9.0	82
	NO	−0.63(0.84)	[−2.28, 1.02]	0.29(0.11)	[0.07, 0.51]	0.55	7.0–8.4	18
$\lg(L/W) = a + b \times M_w$	ALL	−0.78(0.43)	[−1.62, 0.06]	0.14(0.06)	[0.02, 0.26]	0.22	7.0–9.0	131
	SS	−1.23(1.31)	[−3.80, 1.34]	0.22(0.17)	[−0.11, 0.55]	0.23	7.0–8.6	31
	TH	−0.81(0.42)	[−1.63, 0.01]	0.14(0.05)	[0.04, 0.24]	0.27	7.0–9.0	82
	NO	−0.75(0.84)	[−2.40, 0.90]	0.14(0.11)	[−0.08, 0.36]	0.30	7.0–8.4	18
$\lg(S) = a + b \times M_w$	ALL	−3.73(0.73)	[−5.16, −2.30]	0.95(0.09)	[0.77, 1.13]	0.67	7.0–9.0	129
	SS	−2.32(1.59)	[−5.44, 0.80]	0.77(0.21)	[0.36, 1.18]	0.57	7.0–8.6	31
	TH	−4.63(0.99)	[−6.57, −2.69]	1.07(0.13)	[0.82, 1.32]	0.69	7.0–9.0	80
	NO	−2.01(1.24)	[−4.44, 0.42]	0.72(0.16)	[0.41, 1.03]	0.75	7.0–8.4	18
$\lg(D_{\max}) = a + b \times M_w$	ALL	−2.83(0.54)	[−3.89, −1.77]	0.46(0.07)	[0.32, 0.60]	0.62	7.0–9.0	74
	SS	−3.62(1.67)	[−6.89, −0.35]	0.59(0.22)	[0.16, 1.02]	0.54	7.1–8.6	20
	TH	−2.88(0.59)	[−4.04, −1.72]	0.46(0.08)	[0.30, 0.62]	0.68	7.0–9.0	45
	NO	−3.03(0.79)	[−4.58, −1.48]	0.49(0.10)	[0.29, 0.69]	0.87	7.0–8.4	9
$\lg(\overline{D}) = a + b \times M_w$	ALL	−3.48(0.57)	[−4.60, −2.36]	0.51(0.07)	[0.37, 0.65]	0.65	7.0–9.0	68
	SS	−5.78(1.25)	[−8.23, −3.33]	0.81(0.16)	[0.50, 1.12]	0.76	7.0–8.6	20
	TH	−1.76(0.62)	[−2.98, −0.54]	0.29(0.08)	[0.13, 0.45]	0.52	7.0–9.0	39
	NO	−5.54(1.49)	[−8.46, −2.62]	0.78(0.20)	[0.39, 1.17]	0.83	7.0–8.2	9
$\lg(\overline{D}/D_{\max}) = a + b \times M_w$	ALL	0.89(0.64)	[−0.36, 2.14]	−0.06(0.08)	[−0.22, 0.10]	−0.15	7.0–9.0	25
	SS	0.28(1.91)	[−3.46, 4.02]	0.02(0.24)	[−0.45, 0.49]	0.04	7.5–8.6	6
	TH	0.07(0.63)	[−1.16, 1.30]	0.04(0.08)	[−0.12, 0.20]	0.15	7.0–9.0	15
	NO	3.76(3.10)	[−2.32, 9.84]	−0.43(0.41)	[−1.23, 0.37]	−0.59	7.1–8.1	4
$\lg(V_r) = a + b \times M_w$	ALL	0.61(0.25)	[0.12, 1.10]	−0.03(0.03)	[−0.09, 0.03]	−0.08	7.0–9.0	110
	SS	0.31(0.50)	[−0.67, 1.29]	0.01(0.06)	[−0.11, 0.13]	0.05	7.0–8.6	33
	TH	0.77(0.35)	[0.08, 1.46]	−0.05(0.04)	[−0.13, 0.03]	−0.15	7.1–9.0	60
	NO	−0.02(0.42)	[−0.84, 0.80]	0.06(0.06)	[−0.06, 0.18]	0.28	7.0–8.4	17
$\lg(\Delta\sigma) = a + b \times M_w$	ALL	−2.81(1.77)	[−6.28, 0.66]	0.47(0.23)	[0.02, 0.92]	0.26	7.0–8.6	59
	SS	−2.83(3.31)	[−9.32, 3.66]	0.46(0.43)	[−0.38, 1.30]	0.27	7.0–8.6	17
	TH	−4.38(2.91)	[−10.08, 1.32]	0.68(0.38)	[−0.06, 1.42]	0.31	7.0–8.3	33
	NO	−0.94(3.03)	[−6.88, 5.00]	0.25(0.40)	[−0.53, 1.03]	0.24	7.0–8.4	9
$\lg(T_R) = a + b \times M_w$	ALL	−1.90(0.50)	[−2.88, −0.92]	0.45(0.07)	[0.31, 0.59]	0.60	7.0–9.0	91
	SS	−1.89(1.46)	[−4.75, 0.97]	0.45(0.19)	[0.08, 0.82]	0.43	7.0–8.6	26
	TH	−1.71(0.61)	[−2.91, −0.51]	0.43(0.08)	[0.27, 0.59]	0.62	7.0–9.0	52
	NO	−1.43(0.99)	[−3.37, 0.51]	0.38(0.13)	[0.13, 0.63]	0.66	7.0–8.2	13

Power denotes the achieved two-sided statistical power for testing a zero correlation at $\alpha = 0.05$.

The statistical significance of each Pearson correlation coefficient was evaluated using a two-tailed t -test at the 0.05 significance level. The correlations of moment magnitude with rupture length, width, area, maximum slip, average slip, and rupture duration were generally statistically significant ($p < 0.05$). In contrast, the correlations between moment magnitude and average rupture velocity were insignificant for all fault-type groups ($p = 0.253$ – 0.789). For stress drop, only the combined dataset showed a marginally significant correlation ($r = 0.26$, $p = 0.047$), whereas the correlations for strike-slip, reverse/thrust, and normal faults were insignificant ($p = 0.079$ – 0.534). The average-to-maximum slip ratio was also not significantly correlated with moment magnitude in any group ($p = 0.410$ – 0.940). Therefore, these weak relationships should be interpreted as an absence of statistically supported linear dependence rather than as meaningful empirical scaling relationships.

Table 1 reports the coefficient estimates, standard errors, 95% confidence intervals, effective sample sizes, Pearson correlation coefficients, p values, and achieved statistical power. Here, L and W are expressed in km, S in km², $D_{\max}$ and $\overline{D}$ in m, V_r in km/s, $\Delta\sigma$ in MPa, and T_R in s. Statistical significance was evaluated using a two-sided test at $\alpha = 0.05$. A power value of 0.80 was regarded as adequate. Relationships with $p \geq 0.05$ or power < 0.80 are treated as exploratory and are not interpreted as established scaling

relationships. In particular, the $D_{\max}/\bar{D}-M_w$ relationship is based on only 25 observations ($r = -0.15$; power = 0.11), and its slope confidence interval includes zero. A statistical power analysis was conducted using the effective sample size and observed correlation coefficient for each regression, with a two-sided significance level of $\alpha = 0.05$. A power value of 0.80 was considered adequate. The relationships of rupture length, rupture area, maximum slip, average slip, and rupture duration generally showed adequate statistical power. In contrast, the relationships involving the average-to-maximum slip ratio, rupture velocity, and stress drop were underpowered, with most power values below 0.80. In particular, the regression between the average-to-maximum slip ratio and moment magnitude had only 25 observations, a correlation coefficient of -0.15 , and a power of 0.11. Its slope confidence interval included zero, indicating that the available sample was insufficient to establish a statistically reliable relationship. Therefore, low-power relationships are interpreted as exploratory rather than conclusive.

For the combined dataset, rupture length, rupture width, rupture area, maximum slip, average slip, and rupture duration are positively correlated with M_w , with correlation coefficients ranging from 0.56 to 0.67. Average rupture velocity and static stress drop show much weaker correlations with M_w ($r = 0.08$ and 0.26 , respectively). Mechanism-specific regressions were calculated for strike-slip, reverse/thrust-, and normal-fault earthquakes. In all three groups, rupture dimensions and slip parameters generally show stronger correlations with M_w than rupture velocity and static stress drop. However, several mechanism-specific regressions have small effective sample sizes or statistical power below 0.80. These results are therefore reported for completeness but should be interpreted cautiously.

3.1. Empirical Relationship Between Source Parameters and Magnitude

3.1.1. $L-M_w$, $W-M_w$ and $S-M_w$

Because rupture area is geometrically related to rupture length and width by $S = L \times W$, the corresponding logarithmic relationships should satisfy $\lg(S) = \lg(L) + \lg(W)$. Accordingly, if $\lg(L) = a_L + b_L M_w$ and $\lg(W) = a_W + b_W M_w$, the geometrically constrained area relationship is $\lg(S) = (a_L + a_W) + (b_L + b_W) M_w$. We therefore compared the independently fitted $S-M_w$ equation with that obtained by summing the fitted $L-M_w$ and $W-M_w$ equations. The derived statistical equations for fault length, width, and area are summarized in Table 2 and Figure 2.

Table 2. Statistical equations for fault length, width, and area derived from least squares fitting.

Empirical Correlation	Slip Type	Statistical Equation	Correlation Coefficient r	Magnitude Range
L and M_w	ALL	$\lg(L) = -2.31 + 0.55 \times M_w$	0.67	7.0–9.0
	SS	$\lg(L) = -1.61 + 0.47 \times M_w$	0.53	7.0–8.6
	TH	$\lg(L) = -2.82 + 0.62 \times M_w$	0.70	7.0–9.0
	NO	$\lg(L) = -1.76 + 0.48 \times M_w$	0.82	7.0–8.4
W and M_w	ALL	$\lg(W) = -1.48 + 0.41 \times M_w$	0.56	7.0–9.0
	SS	$\lg(W) = -0.54 + 0.27 \times M_w$	0.36	7.0–8.6
	TH	$\lg(W) = -1.90 + 0.47 \times M_w$	0.63	7.0–9.0
	NO	$\lg(W) = -0.63 + 0.29 \times M_w$	0.55	7.0–8.4
S and M_w	ALL	$\lg(S) = -3.73 + 0.95 \times M_w$	0.67	7.0–9.0
	SS	$\lg(S) = -2.32 + 0.77 \times M_w$	0.57	7.0–8.6
	TH	$\lg(S) = -4.63 + 1.07 \times M_w$	0.69	7.0–9.0
	NO	$\lg(S) = -2.01 + 0.72 \times M_w$	0.75	7.0–8.4

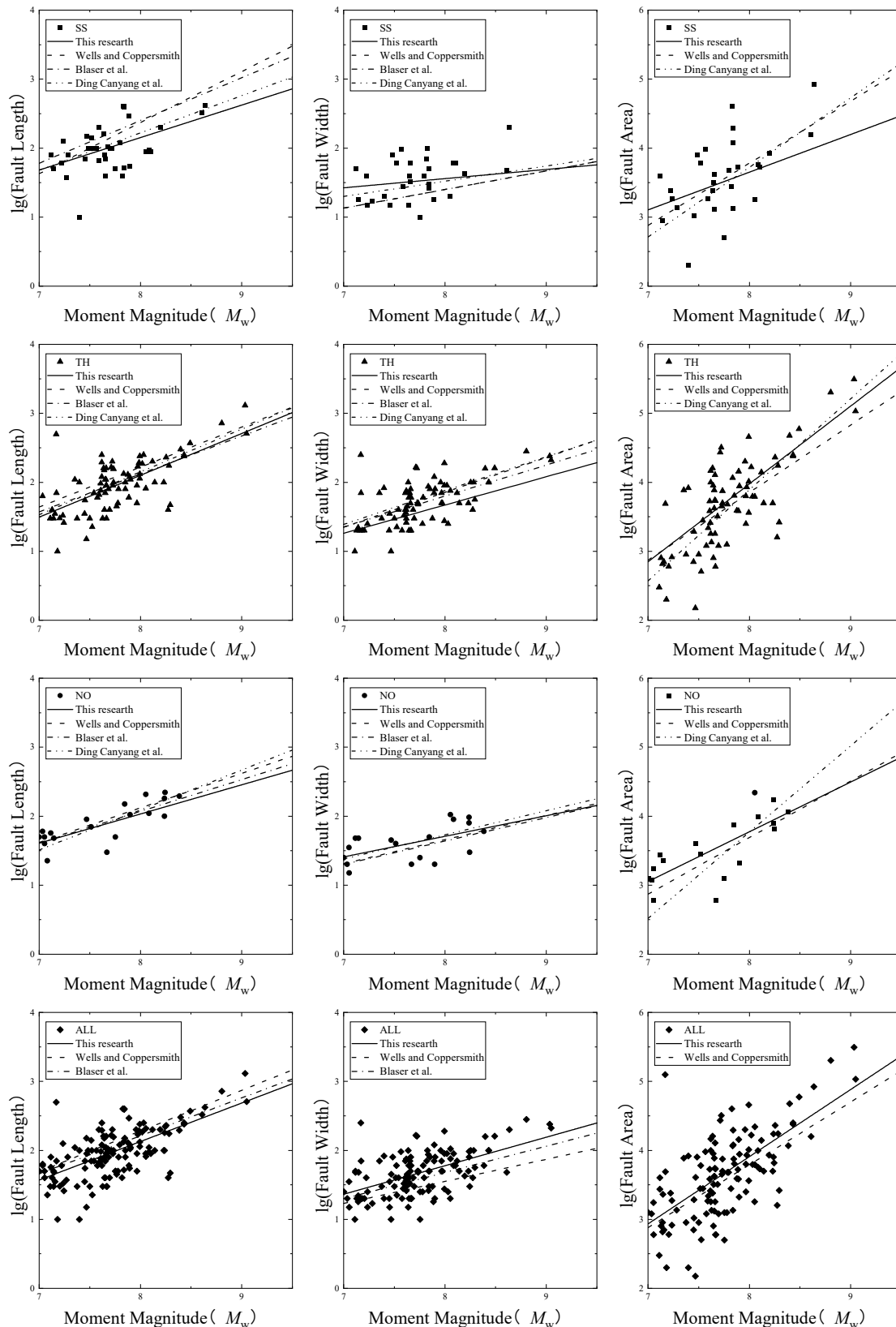


Figure 2. Relationships between fault length, width, area, and moment magnitude for different fault slip types. The solid line represents the empirical relationship between magnitude and rupture parameters derived in this study for normal, reverse, strike-slip, and unspecified fault types. The dashed, dotted, and double-dotted lines correspond to the empirical results of Wells and Coppersmith [4], Blaser et al. [5], and Ding et al. [9], respectively.

For all events, the summed relationship is $\lg(S) = -3.79 + 0.96 M_w$, compared with the independently fitted relationship $\lg(S) = -3.73 + 0.95 M_w$. The corresponding relationships are $-4.72 + 1.09 M_w$ and $-4.63 + 1.07 M_w$ for thrust-fault earthquakes, and $-2.39 + 0.77 M_w$ and $-2.01 + 0.72 M_w$ for normal-fault earthquakes. Over their respective magnitude ranges, these equations yield only small differences, indicating approximate geometric consistency.

The equations are not expected to be exactly identical because the available sample sizes differ among rupture length, width, and area ($n = 146, 131$, and 129 , respectively), and some published rupture areas were reported independently rather than calculated directly from the corresponding length and width. Nevertheless, independent regression does not impose exact geometric consistency, and a constrained formulation should be preferred when a mutually consistent set of scaling equations is required.

For fault rupture length, within the magnitude range of 7.0 to 8.4 for normal fault-type earthquakes, the results obtained in this study show no significant differences compared to those of Ding [9], Blaser et al. [5], and Wells and Coppersmith [4]. The L – M_w relationship for strike-slip faults derived by Wells and Coppersmith [4] and Blaser et al. [5] is similar, and the results in this study align closely with those of Ding et al. [9]. In the magnitude range of 7.0 to 8.5 for reverse fault-type earthquakes, the results of this study are in close agreement with those of Blaser et al. [5] and Ding et al. [9], while for the 8.5 to 9.1 magnitude range, the relationships obtained by Wells and Coppersmith [4] and Ding et al. [9] for reverse faults are comparable, with the results of this study falling between those of Wells and Coppersmith [4] and Blaser et al. [5]. For the empirical relationship that does not distinguish fault types, the L – M_w relationship derived in this study shows a notable deviation from that of Wells and Coppersmith [4], with the results of Blaser et al. [5] lying in between the two.

For fault rupture width, the results for normal faults in this study align with those reported by other scholars. For strike-slip faults, the W – M_w relationship derived by Wells and Coppersmith [4] and Blaser et al. [5] is identical. In the magnitude range of 7.0 to 8.2, the results obtained in this study show a notable deviation from those of Wells and Coppersmith [4], but the discrepancy diminishes as magnitude increases. After magnitude 8.2, the results of this study show no significant differences when compared to those of Wells and Coppersmith [4], Blaser et al. [5], and Ding et al. [9]. For reverse faults, the results of this study exhibit a clear divergence from the final empirical relationships, especially the W – M_w relationship proposed by Wells and Coppersmith [4], and this difference is also reflected in the empirical relations that do not distinguish between fault types.

Regarding fault rupture area, both the strike-slip fault and the empirical relationship that does not distinguish fault types show marked discrepancies with existing relationships. In the 7.0 to 8.3 magnitude range, the S – M_w empirical relationship for reverse faults derived in this study is in close agreement with the results of other scholars. However, in the 8.3 to 9.3 magnitude range, as the magnitude increases, the results of this study diverge more clearly from those of other studies. Conversely, the empirical relationship for normal faults in this study is similar to the results of Wells and Coppersmith [4].

3.1.2. $D_{\max}$ – M_w and $\bar{D}$ – M_w

The maximum and average slip values obtained in this study are derived from published seismic survey literature, where related parameters such as fault mechanisms, slip types, and slip amounts were obtained through finite fault simulations. Therefore, this study focuses on the slip amounts on finite faults. According to the fitting results in Table 3, the correlation coefficients between maximum slip, average slip, and moment magnitude range from 0.52 to 0.87, indicating a strong correlation. Furthermore, a comparison with existing studies (Figure 3) reveals that the average slip versus moment magnitude relation-

ship derived by Somerville et al. [2] does not differentiate slip types. The results obtained in this study for all fault types align with those of Somerville et al. [2], though significant deviations are observed for strike-slip, reverse, and normal faults. Additionally, Wang [11] classified faults into strike-slip, dip-slip, and all fault categories. The $\bar{D}$ – M_w empirical relationship for strike-slip and all fault types derived in this study shows clear differences from the results of Wang [11].

Table 3. Statistical equations for maximum and average slip derived from least squares fitting.

Empirical Correlation	Slip Type	Statistical Equation	Correlation Coefficient r	Magnitude Range
$D_{\max}$ and M_w	ALL	$\lg(D_{\max}) = -2.83 + 0.46 \times M_w$	0.62	7.0–9.0
	SS	$\lg(D_{\max}) = -3.62 + 0.59 \times M_w$	0.54	7.1–8.6
	TH	$\lg(D_{\max}) = -2.88 + 0.46 \times M_w$	0.68	7.0–9.0
	NO	$\lg(D_{\max}) = -3.03 + 0.49 \times M_w$	0.87	7.0–8.4
$\bar{D}$ and M_w	ALL	$\lg(\bar{D}) = -3.48 + 0.51 \times M_w$	0.65	7.0–9.0
	SS	$\lg(\bar{D}) = -5.78 + 0.81 \times M_w$	0.76	7.0–8.6
	TH	$\lg(\bar{D}) = -1.76 + 0.29 \times M_w$	0.52	7.0–9.0
	NO	$\lg(\bar{D}) = -5.54 + 0.78 \times M_w$	0.83	7.0–8.2

3.1.3. V_r – M_w , $\Delta\sigma$ – M_w and T_R – M_w

Compared to previous studies, this paper expands the database by incorporating three additional parameters: average rupture velocity, stress drop, and rupture duration. Empirical relationships with magnitude were then derived for each parameter, categorized by fault type. As shown in Table 4, the correlation coefficient (r) between average rupture velocity and stress drop is less than 0.31, indicating a minimal correlation, which is consistent with the conclusions of Somerville et al. [2]. For rupture duration, the T_R – M_w empirical relationship for strike-slip faults shows a weak correlation, with a correlation coefficient (r) of 0.43. In contrast, for reverse faults, normal faults, and the combined fault type category, the correlation coefficients range from 0.60 to 0.66, indicating a strong correlation.

Table 4. Statistical equations for rupture velocity, stress drop, and duration derived from least squares fitting.

Empirical Correlation	Slip Type	Statistical Equation	Correlation Coefficient r	Magnitude Range
V_r and M_w	ALL	$\lg(V_r) = 0.61 - 0.03 \times M_w$	−0.08	7.0–9.0
	SS	$\lg(V_r) = 0.31 + 0.01 \times M_w$	0.05	7.0–8.6
	TH	$\lg(V_r) = 0.77 - 0.05 \times M_w$	−0.15	7.1–9.0
	NO	$\lg(V_r) = -0.02 + 0.06 \times M_w$	0.28	7.0–8.4
$\Delta\sigma$ and M_w	ALL	$\lg(\Delta\sigma) = -2.81 + 0.47 \times M_w$	0.26	7.0–8.6
	SS	$\lg(\Delta\sigma) = -2.83 + 0.46 \times M_w$	0.27	7.0–8.6
	TH	$\lg(\Delta\sigma) = -4.38 + 0.68 \times M_w$	0.31	7.0–8.3
	NO	$\lg(\Delta\sigma) = -0.94 + 0.25 \times M_w$	0.24	7.0–8.4
T_R and M_w	ALL	$\lg(T_R) = -1.90 + 0.45 \times M_w$	0.60	7.0–9.0
	SS	$\lg(T_R) = -1.89 + 0.45 \times M_w$	0.43	7.0–8.6
	TH	$\lg(T_R) = -1.71 + 0.43 \times M_w$	0.62	7.0–9.0
	NO	$\lg(T_R) = -1.43 + 0.38 \times M_w$	0.66	7.0–8.2

3.2. Empirical Relationships Between Source Parameters

3.2.1. Aspect Ratio and Slide Type

The aspect ratio represents the ratio of fault length (L) to fault width (W) in an earthquake rupture. Fault length typically refers to the horizontal extension of the rupture surface, while fault width corresponds to the rupture depth or the surface width perpen-

dicular to the fault plane. This length-to-width ratio is a critical geometric parameter in the rupture process of an earthquake source, as it directly influences the rupture mode, energy release patterns, and the propagation characteristics of seismic waves. Different slip types manifest distinct fault geometries, and the aspect ratio, as a key descriptor of fault structure, offers insights into rupture characteristics, stress field distribution, and the geological context of earthquakes.

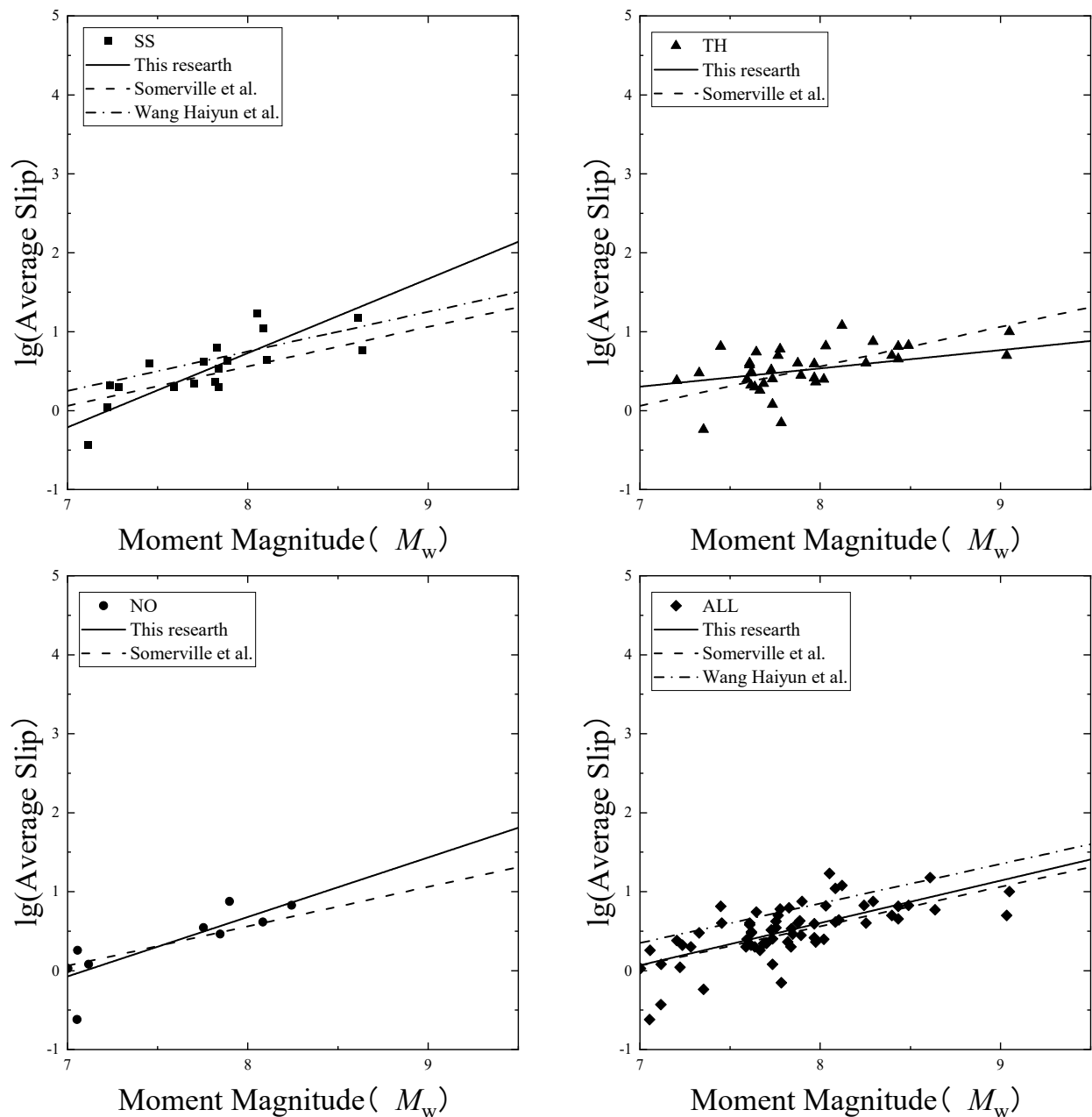


Figure 3. Relationship between fault mean slip and moment magnitude for different fault slip types. The solid line illustrates the empirical relationship between fault average slip and moment magnitude for normal, reverse, and strike-slip faults derived in this study. The dashed line represents the empirical relationship from Somerville et al. [2], while the dotted line corresponds to the empirical relationship from Wang [11].

Leonard [12], in his study of the geometric properties of strike-slip, reverse-slip, and normal faults, proposed that strike-slip faults typically exhibit the highest aspect ratios, ranging from 2:1 to 5:1, while reverse-slip and normal faults generally have aspect ratios between 1:1 and 2:1, and may even fall below 1:1 in some deep, large earthquakes. The analysis presented in this paper (Figure 4) reveals that the average aspect ratio is 3.97 for strike-slip faults, 2.05 for reverse-slip faults, and 2.43 for normal faults, with the latter two values falling within the expected range of 1:1 to 2:1.

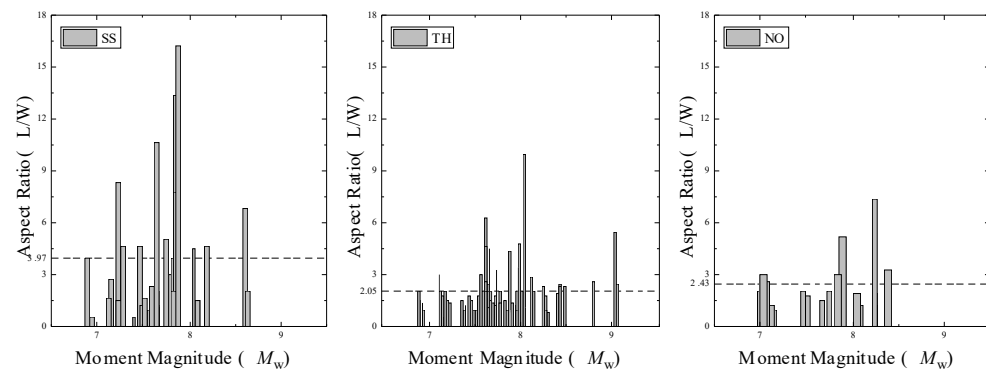


Figure 4. Comparison of fault aspect ratios across different fault slip types. The dash lines represent the average value.

3.2.2. Average and Maximum Slip

During a typical earthquake rupture, the maximum slip is generally 1.5 to 2 times the average slip. Mai and Beroza [13] highlighted that the distribution of seismic slip is highly heterogeneous, and the ratio of average slip to maximum slip serves as a key indicator of this inhomogeneity, with the maximum slip often significantly exceeding the average slip. In this study, we analyze the relationship between average slip and maximum slip for 25 seismic events, and find that the ratio of maximum slip to average slip predominantly falls within the range of 1.5 to 3.5, with an average value of 3.18 (Figure 5).

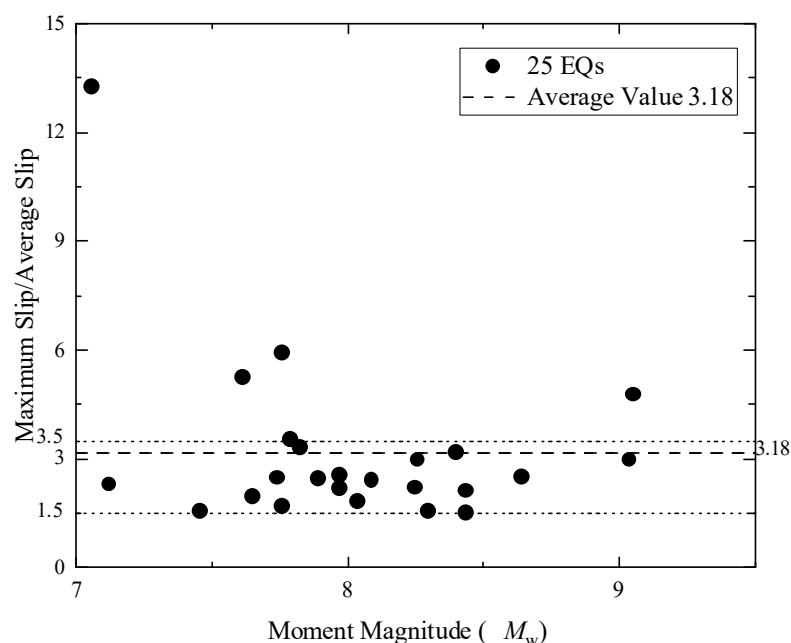


Figure 5. Ratio of maximum and average slip to moment magnitude.

3.2.3. Stress Drop, Average Rupture Velocity and Seismic Source Depth

The empirical relationships between stress drop, rupture velocity, and source depth have been extensively studied by Abercrombie et al. [14], Uchide et al. [15], and Jiang et al. [16], who concluded that both stress drop and rupture velocity increase systematically with increasing source depth. However, the seismic events examined in these studies were predominantly of low magnitude, ranging from $0 \leq M \leq 5.0$. In contrast, this study analyzes the statistical relationships of stress drop for 59 strong-motion seismic events and finds that, for both shallow and deep-source earthquakes, the stress drop exhibits little variation with increasing source depth. This observation aligns with the findings of Yenier and Atkinson [17,18]. Additionally, the statistical analysis of rupture velocity for 110 strong earthquakes reveals that rupture velocity remains relatively constant with increasing source depth (Figure 6).

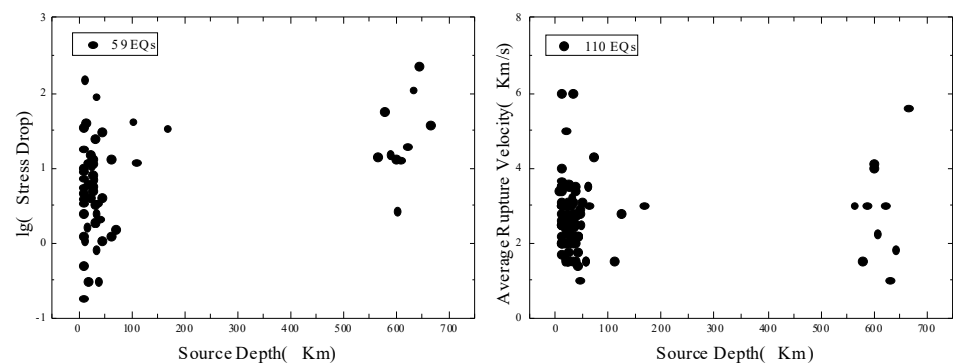


Figure 6. Ratio of stress drop, rupture velocity, and seismic source depth.

4. Discussion

The prediction of strong ground motion induced by destructive earthquakes is inherently fraught with uncertainties. Statistical methods provide an optimal framework for addressing these random uncertainties [19]. In this study, we undertake a comprehensive analysis and comparison of the empirical relationships between multiple source parameters and earthquake magnitude, while also investigating the interdependencies among various source parameters. Through statistical examination of a large dataset of earthquake events, we derive a set of empirical formulas and quantify the resulting correlations. In doing so, we explore two key aspects: the empirical relationship between source parameters and moment magnitude, and the interrelationships among the source parameters themselves.

Beyond describing the statistical relationships, the following discussion examines their possible physical causes in terms of fault geometry, faulting mechanism, rupture propagation, stress conditions, source depth, and heterogeneity of the fault medium. In particular, Sections 4.1 and 4.2 discuss why rupture dimensions, fault slip, rupture velocity, stress drop, and rupture duration exhibit different scaling behaviors among strike-slip, thrust, and normal-fault earthquakes. These interpretations are intended to connect the statistical observations with the underlying tectonic and rupture processes, although the present dataset does not permit definitive causal attribution.

4.1. Comparative Analysis of the Empirical Relationship Between Seismic Source Parameters and Moment Magnitude

The observed correlations of rupture length, width, area, and average slip with M_w are physically expected because these parameters enter directly into the definition of seismic moment. Based on the analysis in Section 3.1, we establish empirical relationships between various seismic source parameters and moment magnitudes, including $L-M_w$, $W-M_w$, $S-M_w$, $D_{\max}-M_w$, V_r-M_w , $\Delta\sigma-M_w$, and T_R-M_w . Overall, the relationships between seismic

source parameters and moment magnitude exhibit general consistency across different fault types, while also displaying distinct characteristics.

The logarithms of rupture length, width, and area are positively related to M_w ; equivalently, these rupture dimensions increase approximately exponentially with M_w . The correlations are stronger for the normal- and reverse/thrust-fault groups than for the strike-slip group in the present dataset. These differences may reflect fault geometry, seismogenic thickness, tectonic setting, sample composition, and source-modeling methods. However, the present statistical analysis does not establish a unique causal explanation for the observed differences. In particular, reverse faulting exhibits a stronger correlation with fault width due to the greater vertical component of rupture in reverse faulting, where an increase in width significantly influences the rupture area, and, by extension, the amount of energy released. For normal faults, the moment magnitude shows a stronger correlation with fault width and area, as fault tilting and extension result in larger rupture areas, especially when fault width increases markedly [20]. Consequently, for earthquakes of the same magnitude, the rupture area tends to be larger in normal faults, and moment magnitude exhibits a more pronounced dependence on fault area, as reported by Mai and Beroza [3]. In contrast, for strike-slip faulting events, the correlation between fault scale and moment magnitude diverges from previous studies. Strike-slip earthquakes primarily involve lateral shear motions rather than rupture perpendicular to the fault, and the empirical relationships derived for these events may differ due to variations in fault geometry, stress conditions, and the mechanical properties of the fault medium [21]. Furthermore, discrepancies may arise from differences in the datasets, earthquake catalogs, or the range of seismic events analyzed in prior studies, leading to variations in statistical outcomes. Differences between the present relationships and previous scaling models may partly reflect the regression method. Thingbaijam et al. [6] used general orthogonal regression to account for uncertainties in both magnitude and source parameters, whereas the present study uses OLS to estimate source parameters conditional on M_w . Consequently, our equations should be interpreted as dataset-specific predictive relationships rather than mutually self-consistent, regression-method-independent scaling laws. The absence of uniform event-specific uncertainty estimates in the compiled literature prevented a fully uncertainty-weighted orthogonal regression and represents a limitation of this study.

There is a strong correlation between the maximum and average slip and the moment magnitude, with correlation coefficients ranging from 0.52 to 0.87. This result shows some deviation from previous studies. Notably, when compared to the findings of Somerville et al. [2], our study's classification of different fault types reflects more detailed slip characteristics, whereas Somerville et al. [2] did not differentiate between slip types and instead provided a general empirical relationship. When we consider the average slip and moment magnitude without distinguishing slip types, our results are largely consistent with those of Somerville et al. [2]. However, given the significant differences in the slip mechanisms across fault types, our study's analysis of normal, reverse, and strike-slip faults results in slip-moment magnitude relationships that show greater deviation from Somerville et al. [2]. Additionally, when compared to the study by Wang [11], which also classified strike-slip, oblique-slip, and all fault types, our results still exhibit notable differences. These discrepancies are likely due to differences in the study focus, model parameter selection, and data sources.

The analysis of the V_r - M_w , $\Delta\sigma$ - M_w , and T_R - M_w relationships demonstrates the complex interactions between average rupture velocity, stress drop, rupture duration, and moment magnitude. The statistical relationships between average rupture velocity, stress drop, and moment magnitude reveal a weak correlation with moment magnitude in the existing database. For rupture velocity, the variation in average rupture velocity is influ-

enced by multiple factors, such as the fault geometry, medium heterogeneity, and local stress conditions along the rupture propagation path. These factors result in high spatial and temporal variability in rupture velocity during an earthquake, thus weakening its simple log-linear relationship with moment magnitude. Stress drop estimates are also affected by various factors, including the source depth, fault surface friction characteristics, and other local conditions [22]. In addition, although all compiled values were treated as source-averaged static stress drop, they were obtained from different published sources and were not necessarily estimated using identical source models or inversion procedures. This methodological heterogeneity may contribute substantially to the scatter in the $\Delta\sigma$ – M_w relationship. Therefore, the weak correlation reported here should be interpreted cautiously and should not be regarded as evidence for the absence of an underlying physical relationship between static stress drop and magnitude. In different seismic events, variations in fault slip modes and rupture processes can lead to significant differences in stress drop. Moreover, different fault types (such as strike-slip and reverse faults) may have different stress states, making it difficult to capture a consistent empirical relationship between stress drop and magnitude.

The correlation between rupture duration and moment magnitude is more pronounced for reverse and normal fault earthquakes, while it is weaker for strike-slip fault events. Different fault types exhibit distinct dynamic characteristics during rupture. Strike-slip faults typically have longer rupture lengths but shallower rupture depths, leading to shorter and more variable rupture durations. In contrast, reverse and normal faults are associated with larger vertical movements and may extend deeper, resulting in a more stable relationship between rupture duration and moment magnitude. Larger magnitude earthquakes, particularly those involving reverse and normal faults, generally have longer rupture durations due to their larger rupture areas and propagation paths. This observation aligns with classical seismic source theory, which suggests a positive correlation between rupture duration, seismic energy, and earthquake size. Consequently, the T_R – M_w empirical relationship for reverse and normal fault events shows a strong correlation with moment magnitude.

4.2. Discussion of Interrelationships Between Seismic Source Parameters

Section 3.2 examines the relationships of rupture aspect ratio with faulting mechanism, maximum slip with average slip, and source depth with rupture velocity and static stress drop. The insights gained from these relationships are essential for a deeper understanding of the dynamic processes involved in earthquake rupture.

Rupture aspect ratio varies among faulting mechanisms. Strike-slip earthquakes have the largest mean length-to-width ratio (3.97), consistent with rupture propagation predominantly along strike and limitation of rupture width by seismogenic thickness. Reverse/thrust- and normal-fault earthquakes have lower mean ratios of 2.05 and 2.43, respectively. The normal-fault mean slightly exceeds 2:1 and should therefore not be described as falling within a 1:1–2:1 range. These group differences are consistent with variations in fault geometry, although tectonic setting and sample composition may also contribute.

The analysis of 25 seismic events in this study reveals that the ratio of the maximum to the average fault slip ranges from 1.5 to 3.5, with a mean value of 3.18, reflecting the highly uneven distribution of slip during earthquake rupture. This ratio serves as a crucial indicator of such unevenness: a larger ratio suggests that slip is concentrated in localized regions, leading to a more uneven release of energy along the rupture plane. Consistent with the findings of Mai and Beroza [13], this study also observes that the maximum slip is generally much larger than the average slip, indicating the significant impact of

concentrated slip zones on earthquake rupture behavior. The uneven distribution of slip is intricately linked to the fault geometry, stress state, and rupture dynamics, and has important implications for seismic modeling and damage assessment [13].

The relationship between stress drop, rupture velocity, and source depth provides further insight into the dynamic characteristics of earthquake rupture. The results show that, at shallow depths, the surrounding rocks are more fragmented and weaker, with lower material strength, which impedes the rupture propagation velocity. In such cases, rupture velocity is relatively low. The heterogeneity of near-surface rocks also contributes to slower rupture speeds. The higher degree of rock fragmentation at shallow depths can introduce localized frictional resistance along the rupture plane, further slowing the rupture velocity [23]. Given that most of the seismic events analyzed in this study are shallow-focus earthquakes, the rupture velocity exhibits little variation with increasing source depth. Additionally, a certain degree of correlation is observed between source depth and stress drop: deeper-focus earthquakes tend to have higher stress drops, while shallow-focus earthquakes typically exhibit lower stress drops. This may be related to the differing physical conditions (e.g., temperature, pressure) at various depths in the crust, which influence stress accumulation and release [16].

5. Conclusions

This study provides a literature-based statistical characterization of source parameters for 165 $M_w \geq 7.0$ earthquakes. Because parameter availability is incomplete and the compiled studies use heterogeneous source models and inversion methods, the fitted equations should be interpreted as dataset-specific empirical relationships rather than universally applicable global scaling laws. The principal findings are summarized below.

Source parameters and moment magnitude: The logarithms of rupture length, rupture width, rupture area, maximum slip, and average slip generally increase linearly with M_w . These relationships are statistically significant for most groups, although their strength varies with faulting mechanism and effective sample size.

Rupture velocity, static stress drop, and rupture duration: Average rupture velocity and static stress drop show weak and mostly statistically insignificant relationships with M_w . These regressions should therefore be regarded as exploratory. Rupture duration is more strongly correlated with M_w for reverse/thrust- and normal-fault earthquakes than for strike-slip earthquakes.

Rupture aspect ratio: Strike-slip earthquakes have a mean length-to-width ratio of 3.97, compared with 2.05 and 2.43 for reverse/thrust- and normal-fault earthquakes, respectively. These results indicate broader rupture-width development in the latter two groups, but they do not demonstrate a unique causal mechanism.

Slip Distribution: Analysis of 25 seismic events reveals that the ratio of maximum to average fault slip is concentrated between 1.5 and 3.5, with a mean value of 3.18. This indicates a significant unevenness in the slip distribution during seismic rupture. Larger ratios suggest that slip is more concentrated in localized areas, with a more uneven release of energy along the rupture plane. The maximum slip is typically much greater than the average slip, underscoring the importance of localized rupture zones in seismic behavior.

Stress Drop, Rupture Velocity, and Source Depth: The relationship between stress drop, average rupture velocity, and source depth shows that both stress drop and rupture velocity exhibit little variation with increasing source depth.

The main limitations of this study are the non-random availability of published source models, unequal sample sizes among parameters, heterogeneous inversion methods, and incomplete separation of tectonic settings. Future work should use event-specific

uncertainty estimates, common-event samples, and tectonic-setting-specific regressions to test the robustness of the reported relationships.

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