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New Updated Classification of Shallow Earthquakes Based on Faulting Style

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Abstract

Earthquakes occur on faults and create new faults. They also occur on normal, reverse and strike-slip faults. The aim of this work is to suggest a new unified classification of Shallow depth earthquakes based on the faulting styles, and to characterize each class. The characterization criteria include the maximum magnitude, focal depth, b-constant value, return period and relations between magnitude, focal depth and dip of fault plane. Global Centroid Moment Tensor (GCMT) catalog is the source of the used data. This catalog covers the period from Jan.1976 to Dec. 2017. We selected only the shallow (depth less than 70kms) pure, normal, strike-slip and reverse earthquakes (magnitude ≥ 5) and excluded the oblique earthquakes. The majority of normal and strike-slip earthquakes occurred in the upper crust, while the reverse earthquakes occurred throughout the thickness of the crust. The main trend for the derived b-values for the three classes was: b_{normal} fault>bstrike-slip fault>breverse fault. The mean return period for the normal earthquake was longer than that of the strike-slip earthquakes, while the reverse earthquakes had the shortest period. The obtained results report the relationship between the magnitude and focal depth of the normal earthquakes. A negative significant correlation between the magnitude and dip class for the normal and reverse earthquakes is reported. Negative and positive correlation relations between the focal depth and dip class were recorded for normal and reverse earthquakes, respectively. The suggested classification of earthquakes provides significant information to understand seismicity, seismtectonics, and seismic hazard analysis.

Keywords: faulting; earthquake; magnitude; b-constant; earthquakes classification

تصنيف جديد محدث للهزات الأرضية الضحلة اعتمادا على نمط التصدع

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الخلاصة

تحدث الهزات الأرضية على امتداد الصدوع وينجم عنها صدعا جديدا. تحصل الهزات الأرضية على امتداد الصدوع الأعتيادية والمعكوسة والمضربية. تهدف الدراسة الى اقتراح تصنيف جديد للهزات الأرضية الضحلة اعتمادا على نمط التصدع وتوصيف كل صنف منها. تتضمن معايير التصنيف أقصى مقدار زلزالي، العمق البؤري، قيمة الثابت-b ، فترة اعادة الوقوع، والعلاقات بين المقدار الزلزالي والعمق البؤري وميل مستوى الصدع. أعتمدت الدراسة على الكتالوج الزلزالي (GCMT) كمصدر للبيانات المستخدمة في الدراسة. يغطي هذا الكتالوج المدة من كانون ثاني 1976 الى كانون أول 2017. أختيرت الهزات الأرضية الضحلة (العمق

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البؤري أقل من 70كم) على امتداد اتجاه ميل الصدوع الضحلة والمعكوسة والمضربية ذات المقدار الزلزالي المساوية واكبر من 5 وتم استثناء الهزات ذات الازاحة المائلة. تقع أغلبية هزات الصدوع الاعتيادية والصدوع المضربية في القشرة العليا بينما تحدث هزات الصدوع المعكوسة خلال كامل القشرة الأرضية. أظهرت الدراسة أن قيمة الثابت –b لهزات الصدوع الاعتيادية أعلى من الهزات المضربية وبدورها أعلى من الهزات المعكوسة. كان متوسط فترة اعادة حدوث هزات الصدوع الاعتيادية أطول من مثيلتها لهزات الصدوع المضربية، بينما كانت فترة اعادة حدوث الهزات المعكوسة أقصر. سجلت علاقة ارتباط سالبة معنوية بين المقدار الزلزالي وصنف الميل لهزات الصدوع الاعتيادية والهزات المعكوسة. أظهرت الدراسة ايضا علاقة ارتباط سالبة بين صنف الميل والعمق البؤري لهزات الصدوع الاعتيادية وعلاقة ارتباط موجبة لهزات الصدوع المعكوسة. يزود هذا التصنيف المقترح المهتمين بمعلومات مهمة لفهم الزلزالية والزلزالية التكتونية وتحليل المخاطر الزلزالية.

Introduction

Classification of the objects or features is important in the majority of sciences. Part of scientific research is concerned with determining subclasses, about which general statements can be made with some confidence [1]. In earthquake seismology, seismologists looking at many earthquakes will often get a very good knowledge of some of the earthquake characteristics. It is useful to classify the earthquake immediately so it becomes easy to find particular types of earthquakes later [2].Classifications of earthquakes were introduced based on the purpose. Hajiwara[3] classified the earthquakes according to their magnitude (M), as follows: great earthquake ($M \geq 8$), large earthquake ($7\ M \leq 8$), moderate earthquake ($5 \leq M < 7$), small earthquake ($3< M < 5$), microearthquake ($1 \leq M < 3$), and ultra-microearthquake ($M < 1$). Earthquakes are classified based on the epicentral distance (Δ^o) into: local earthquake ($\Delta < 10^o$), regional earthquake ($10^o < \Delta < 20^o$), and distant earthquake ($>20^o$). Based on the focal depth, earthquakes are classified into: shallow earthquake (0 – 70 km), intermediate earthquake (70 – 300km), and deep earthquake (> 300km). Earthquakes are classified according to the cause as follows: tectonic earthquake, volcanic earthquake, collapse earthquake, explosion earthquake, and manmade (induced) earthquake. Shimazaki[4] classified earthquakes into interplateearthquake (occurs at a tectonic plate boundary) and intraplate earthquake (occurs in a tectonic plate interior).Doglioni[5] classified the induced earthquakes based on their origin into more detailed subclasses, such as graviquake, reinjection quake, hydro fracturing quake, and loading quake. Many authors used terms, such as normal earthquake (graviquake), reverse earthquake, and strike-slip earthquake to indicate earthquakes that occur on normal, reverse, and strike-slip faults, respectively [6-9]. These earthquake subclasses are not cited in the classical literature of earthquakes seismology as a definite classification, as in the classifications mentioned above. The aim of this work is to suggest a new unified earthquake classification based on the faulting style and to provide characterization of each class.

Data and Methods

The used earthquake catalog was extracted from the Global Centroid Moment Tensor, GCMT (http// www.Globalcmt.org/CMTsearch.html). The catalog covers the period from Jan.1976 to Dec.2017.The classification basis of the earthquake is the rake of slip of fault plane. When the slip angles are 0^o or 180^o, 90^o and -90^o, faults are classified into pure strike-slip, pure dip- reverse and pure dip-slip normal, respectively .We selected the shallow (less than 70km) pure normal, reverse, and strike-slip earthquakes as a database of the classification. We also took into account the uncertainties in estimation of the rake of slip (± 5degrees) when selecting earthquakes. In this study, the fault plane solution of 3052 earthquake of Mw ≥ 5 was used to characterize the subclasses of this suggested earthquake classification. The temporal and spatial distributions of the three subclasses are shown in Figures-(1 and 2), respectively. The magnitude of completeness (Mc) of earthquake catalog for each subclass was estimated using the method introduced previously [10]. The Mc of pure normal, reverse and strike earthquake catalogs are 5.1Mw, 5.1Mw, and 5.3Mw, respectively.

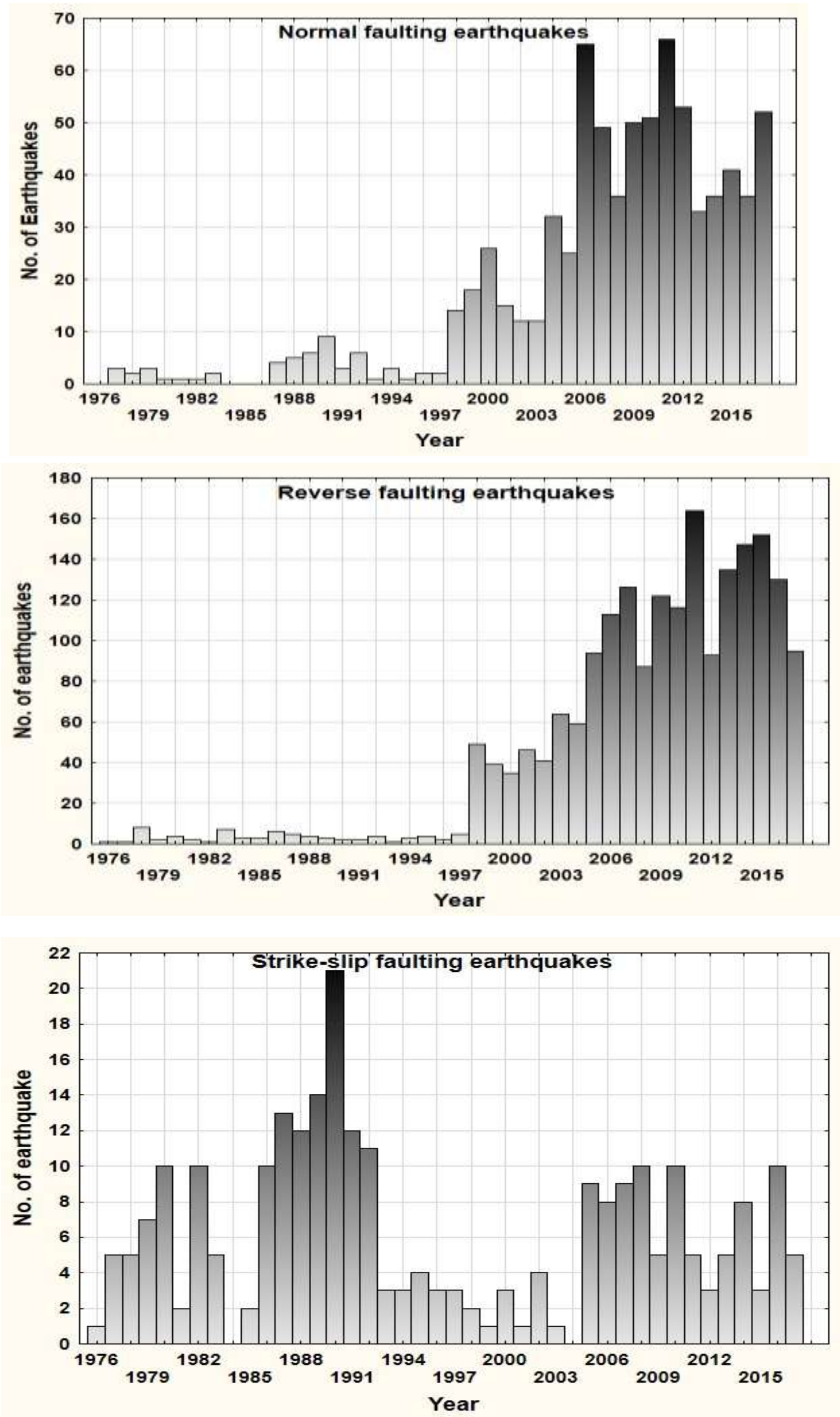


Figure 1-Temporal distribution of the earthquake subclasses.

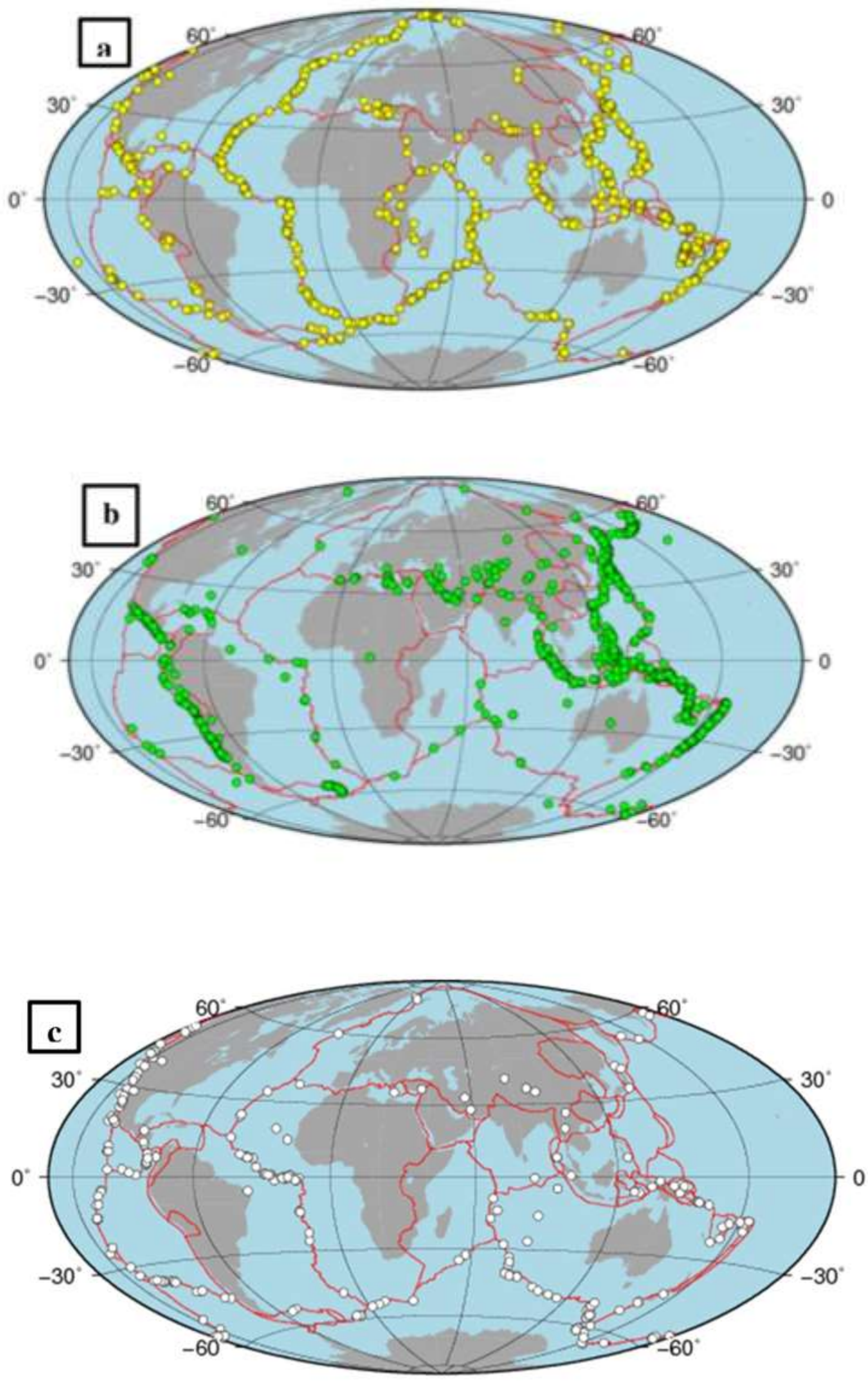


Figure 2-Spatial distribution of the earthquake subclasses. (a) normal faulting earthquakes, (b) reverse faulting earthquakes, and (c) strike-slip faulting earthquakes.

Characterization criteria of the subclasses

The following criteria are used to characterize each subclass:

1. Number of earthquakes
2. Maximum magnitude (M_{max})
3. Focal depth distribution

4. b-constant value
5. Relation between Mw and dip of fault plane
6. Relation between mean of Mw and dip class
7. Relation between depth and dip of fault plane
8. Return period (Mean)

The least squares fitting method was employed to calculate the b-constant value. The return period (T) of earthquake in each subclass was calculated using the Weibull equation [11]

$$Return\ period\ \left(T\right) = \left(n+1\right)/m \quad (1)$$

where n is the number of years of the earthquake catalog and m is the magnitude ranking (in a descending order). The statistical analysis and graphs were conducted using the tibco statistica software (version 13.3), (http//www.tibco.com).

Results

Results of the suggested classification are shown in Figures-(3-6) andsummarized in Table-1. Number of earthquakes for the subclasses tookthe following order: Number $_{(Reverse\ earthquake)}$> Number (Normal earthquake)>Number(Strike –slip earthquake). The main trend for Mmax for the three subclasses was: Mmax(Reverse earthquake)>Mmax(Strike-slip earthquake)>Mmax(Normal earthquake). Most of the pure normal and strike-slip earthquakes occurred in the upper crust while the majority of the pure reverse earthquakes occurred in the lower crust(Figure-3).The remarkable trend for the b-constant values for the three faulting earthquake subclasses was as follows:> b$_{(Normal}$ earthquake)>b(Strike-slip earthquake)>b(Reverse earthquake)(Figure-4). The obtained results show anegative significant relation between Mw and dip of fault plane and an insignificant relation betweenreverse faulting and normal faulting earthquakes, respectively.(Figure-5).Both normal and reverse faulting earthquakes showed negative significant relations between Mw_{mean} and dip class(Figure-5). The relations between depth and dip of the fault plane was anegative significant relation for the normal faulting earthquakes and a positive significant relation for the reverse faulting earthquakes(Figure-6).The order of the mean return period for the three subclasses was: Return period (Normal earthquake)> Return period (Strike-slip earthquake)> Return period (Reverse earthquake).

Table 1-Summary of earthquakes classification based on faulting style

Comparison criteria	Normal faulting earthquakes	Reverse faulting earthquakes	Strike-slip faulting earthquakes
Number of earthquakes	intermediate	large	low
Maximum magnitude	7.7 Mw	9.1 Mw	7.8 Mw
Focal depth distribution	Majority of these earthquakes occur in upper crust.	Majority of these earthquakes occur in lower crust.	Majority of these earthquakes occur in upper crust.
b-constant value	1.07	0.88	1.038
Relation between Mw and dip of fault plane	No significant Insignificant relation	Negative significant relation	
Relation between mean of Mw and dip class	Negative significant relation	Negative significant relation	
Relation between depth and dip of fault plane	Negative significant relation	Positive significant relation	
Return period (Mean)	Large	Low	Intermediate

Discussion

Number of earthquakes Generally, pure reverse, normal and strike-slip faulting earthquakes occur in convergent, divergent and transform fault plate boundaries. Both Pacific and Alps -Himalaya seismic belts are associated with a convergent boundary while mid-oceanic ridges and transform fault seismic belts are related to divergent and transform fault plate boundaries, respectively. The obtained results showed that the number of pure reverse faulting earthquakes is higher than the number of pure normal faulting earthquakes which is, in turn, higher than the number of strike-slip faulting earthquakes(Table-1).The results of this study are consistent with the classical literatures of earthquake seismology. These literatures showed that the majority of the earthquakes occur in the

Pacific and Alps-Himalaya belts (compressional setting) and the remaining occur in the Mid-oceanic ridges belt (tensional setting),while the lowest number occurs in the transform fault belt (strike-slip setting).

Maximum magnitude (Mmax)

The order of Mmax of the three subclass was as follows: Mmax(Reverse earthquake)>Mmax(Strike-slip earthquake)>Mmax(Normal earthquake)(Table-1). The maximum magnitude of normal faulting earthquakes never exceeded the Mmax of the reverse and strike-slip faulting earthquakes, respectively [5]. The convergent plate boundaries are the regions where the largest magnitude of reverse faulting earthquakes occurs [12]. The high b-value of normal faulting earthquakes [6] generates lower magnitude earthquakes than reverse and strike-slip faulting earthquakes [5]. The highest magnitudes of reverse faulting earthquakes compared with those of the strike-slip and normal faulting earthquakes can be explained in terms of that reverse faulting events have the largest potential volume because the ratio between fault length and focal depth is up to 25 times, while it is about 10 and 3 for strike-slip and normal faulting events, respectively [13].

Focal depth distribution

The focal depths of earthquakes provide significant information about the Earth's structure and the tectonic environment where the earthquakes are occurring. The current study showed that the normal and strike-slip faulting earthquakes are concentrated in the upper crust, while the reverse faulting earthquakes occur along the thickness of the crust(Figure-3).In Central Tibet, the strike-slip faulting earthquakes are concentrated in the upper crust while the reverse faulting earthquakes are distributed throughout the thickness of the crust [14].

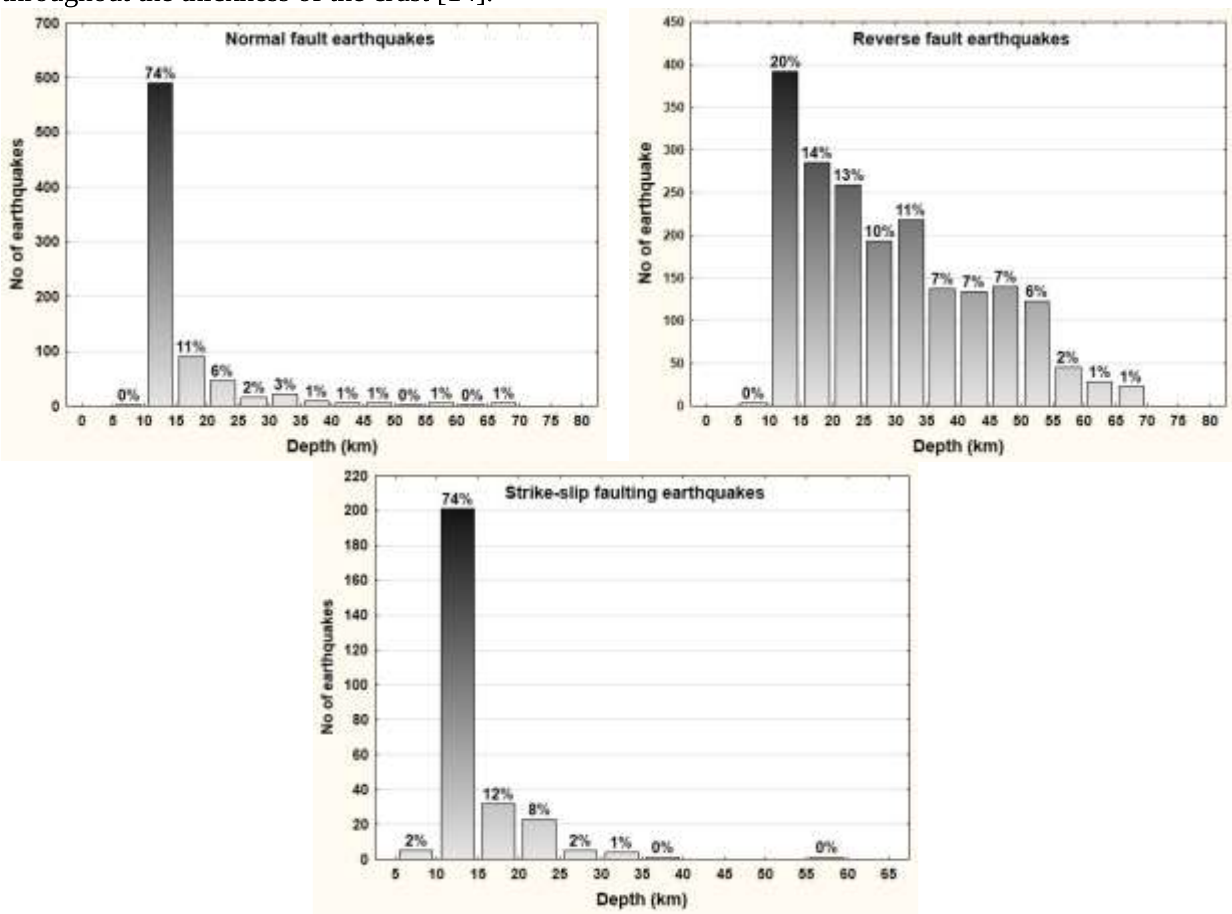


Figure 3-Distribution of depth of the earthquake subclasses.

b -constant value

The b-value in the frequency-magnitude relation provides significant information to understand seismicity, seismotectonics, and seismic hazard analysis. The obtained results show that thrust, strike-slip and normal -faulting earthquakes, occur in regions of low, intermediate, and high b – value, respectively (Figure-4). The previous studies showed that normal faulting events typically show higher b-values, while strike-slip and reverse events have intermediate and low b-values, respectively [6], [7], [9], [15]). The low b – values reflect high differential stress while high b –values indicate low differential stress.

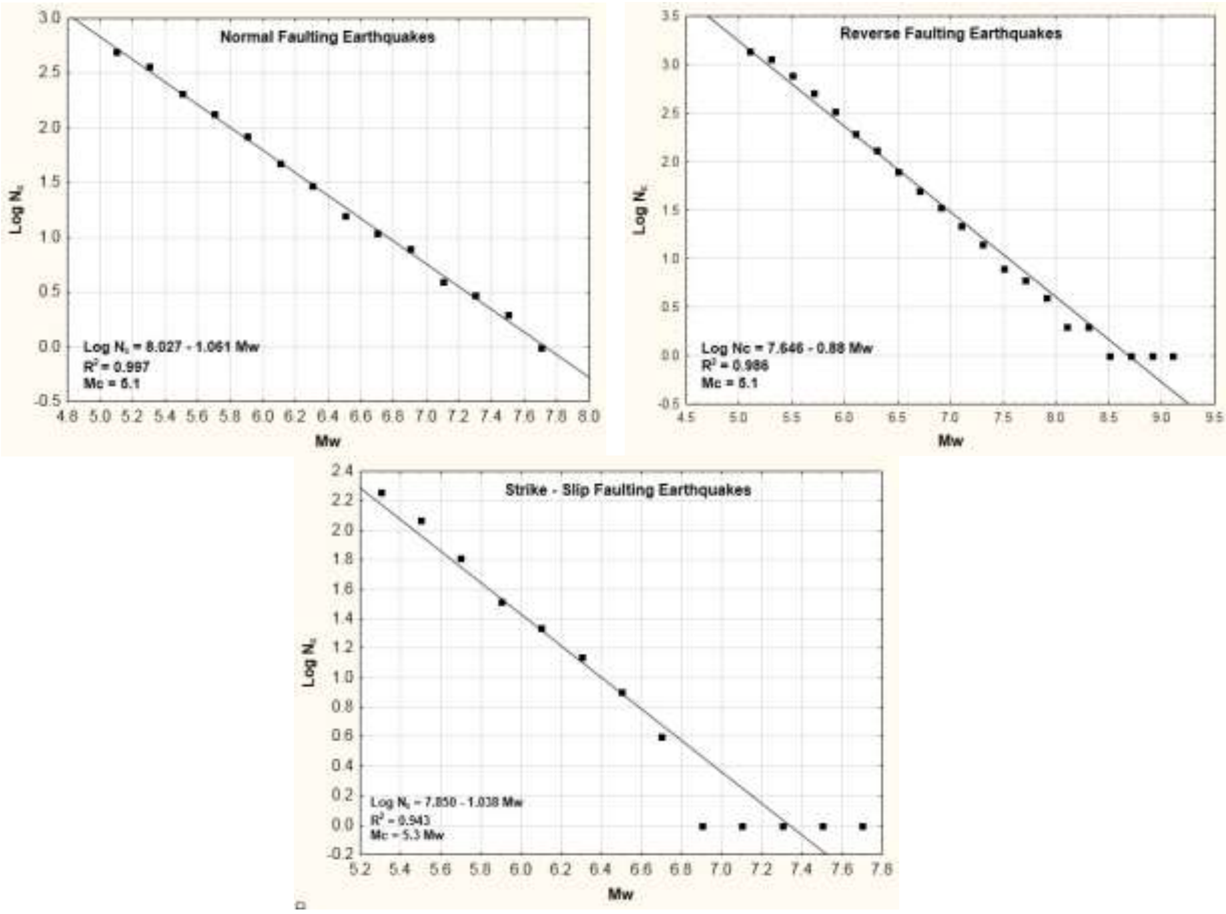
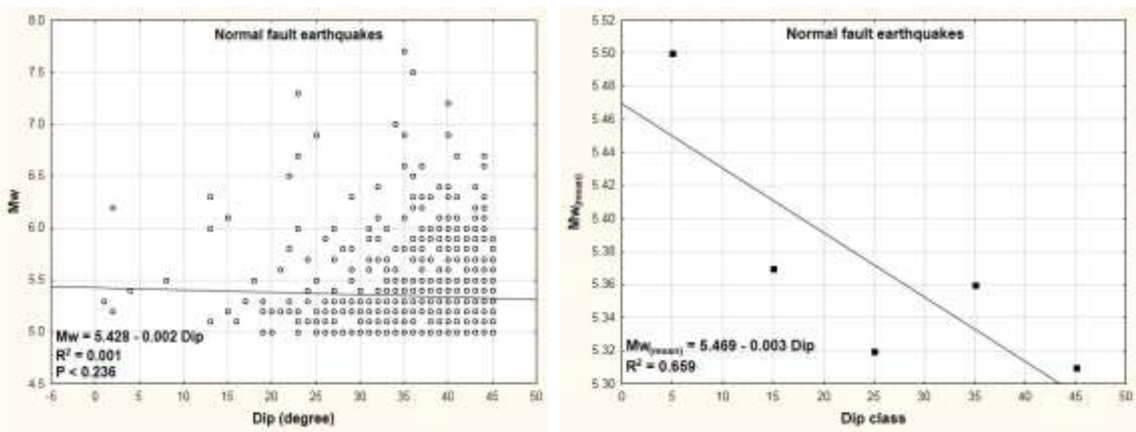


Figure 4-Frequency-magnitude distribution of different faulting styles earthquakes.

Relation between Mw and dip of fault plane To investigate if there is a relation between the magnitude and the dip angle of the faults, we compared the Mw and Mw mean with dip and dip class of normal and reverse faulting earthquakes (Figure-5). The relation between the dip and Mw showed negative insignificant and significant correlations for normal and reverses earthquakes, respectively. The relationships between Mw mean and dip class binned by classes (10^{o}) support that Mw decreases with the increase of fault dip, with a significant correlation for both earthquake subclasses. According to the obtained results, we expect that steeper faults are characterized by earthquakes with higher frequency and lower magnitude in the extensional and compressional tectonic settings. In the Italian extensional setting, the steeper faults are characterized by earthquakes with lower frequency and larger magnitude [13].



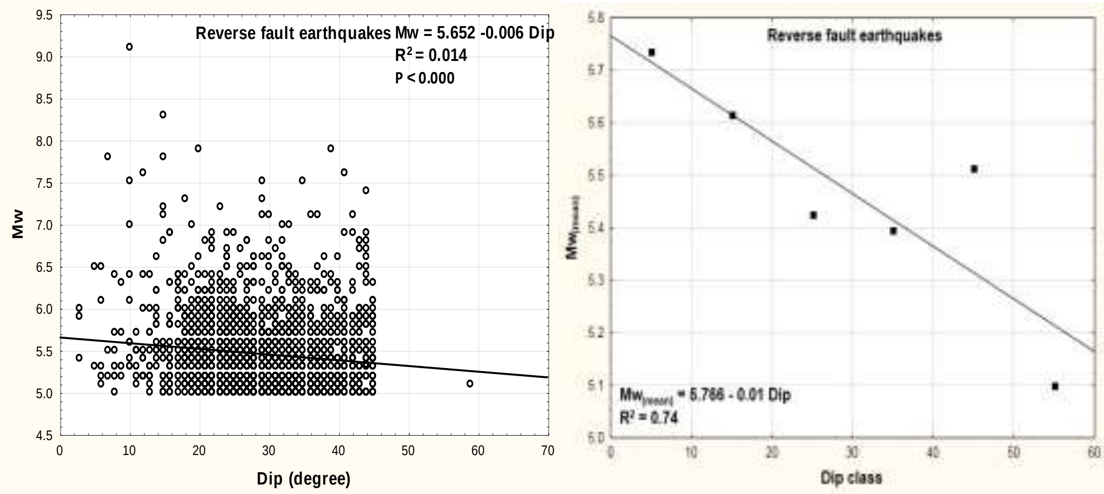


Figure 5-Relation between Mw and dip and Mw mean and dip class for normal and reverse faulting earthquakes.

Relation between depth and dip of fault plane

The relation between depth and dip of fault plane is a negative significant relation for normal faulting earthquakes and a positive significant relation for reverse faulting earthquakes (Figure-6).

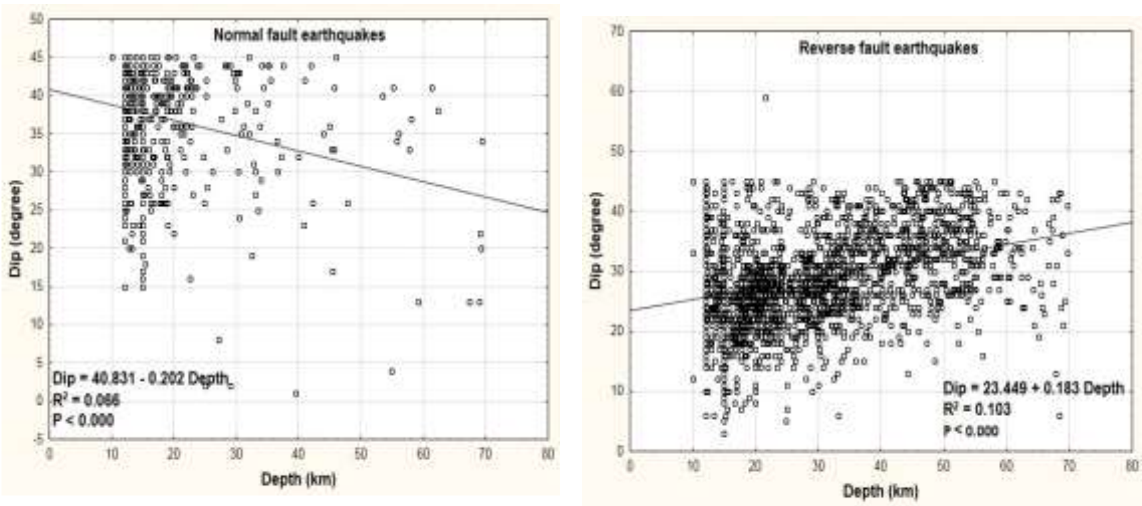


Figure 6-The relation between the dip of fault and the focal depth of normal and reverse faulting earthquakes.

Return period (Mean)

The order of the mean return period for the three subclasses was: Return period $_{(\text{Normal earthquake})}$> Return period $_{(\text{Strike-slip earthquake})}$> Return period $_{(\text{Reverse earthquake})}$.In general, this trend is interpreted in terms of the number of events and the maximum magnitude ranking. The highest magnitude ranking and least number of earthquake are correlated with longer return periods.

Conclusions

The main contribution of this study is the integration of normal, reverse and strike-slip earthquake terms in a new unified classification, similar to other classifications of earthquakes. The new classification of earthquakes is categorized according to the faulting style into three classes, normal, reverse and strike-slip faulting earthquakes. The important contribution of this study is the characterization of each class based on a number of criteria, such as $Mw_{maximum}$, b-constant value, return period and other relations. The suggested classification includes scientific implications and benefits for the public.

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